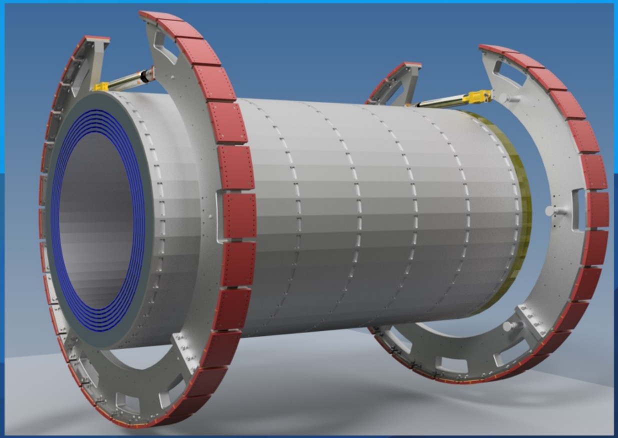
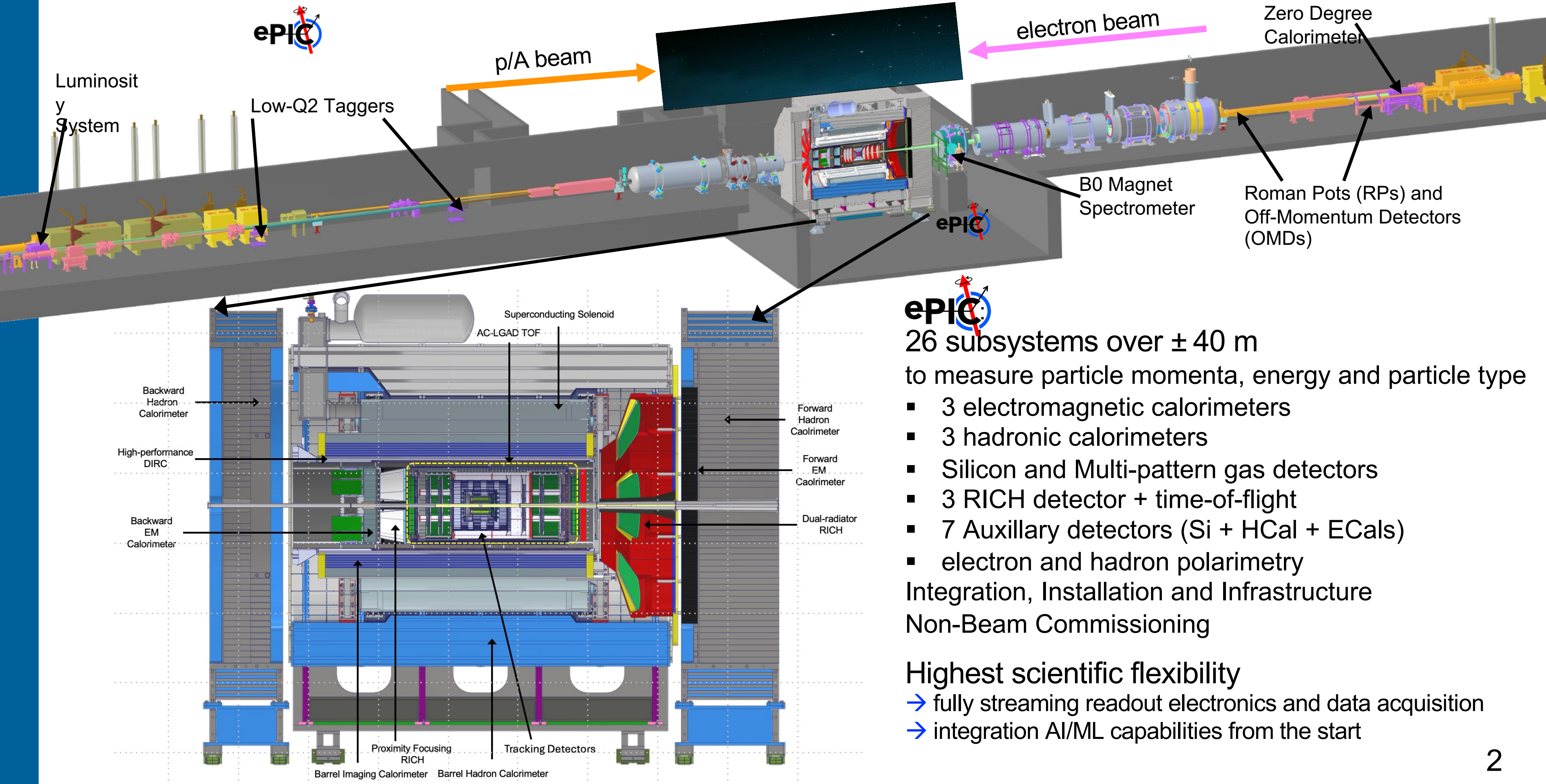
R&D status of the Barrel Imaging Calorimeter for the ePIC experiment



Sanghoon Lim
Pusan National University

ePIC – The EIC General-Purpose Detector



ePIC

26 subsystems over ± 40 m

to measure particle momenta, energy and particle type

- 3 electromagnetic calorimeters
- 3 hadronic calorimeters
- Silicon and Multi-pattern gas detectors
- 3 RICH detector + time-of-flight
- 7 Auxillary detectors (Si + HCal + ECals)
- electron and hadron polarimetry

Integration, Installation and Infrastructure

Non-Beam Commissioning

Highest scientific flexibility

→ fully streaming readout electronics and data acquisition

→ integration AI/ML capabilities from the start

Detector Requirements for BIC

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

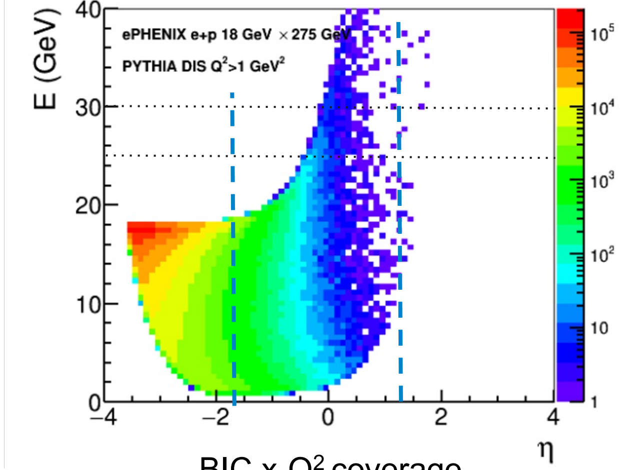
Identify scattered electrons and measure their energy, in high Q^2 events, also decay electrons, e.g., from vector or heavy flavor meson decays, and measure DVCS photons and decay photons

- **Electron ID up to 50 GeV** and down to 1 GeV and below
  - Energy resolution < **10%/√(E) + (2-3)%**
  - High power for **e/π separation down to 1 GeV/c**
- **Photon measurements up to 10 GeV**
- **γ/π⁰ separation up to 10 GeV**
  - Distinguishing two showers with an opening angle down to 30 mrad

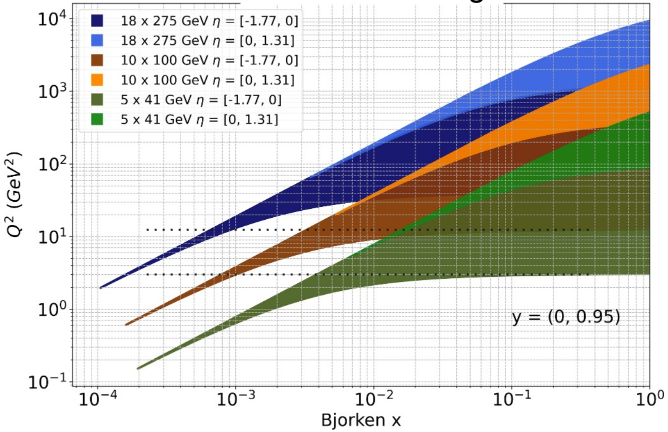
Assist with muon identification

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

DIS electrons



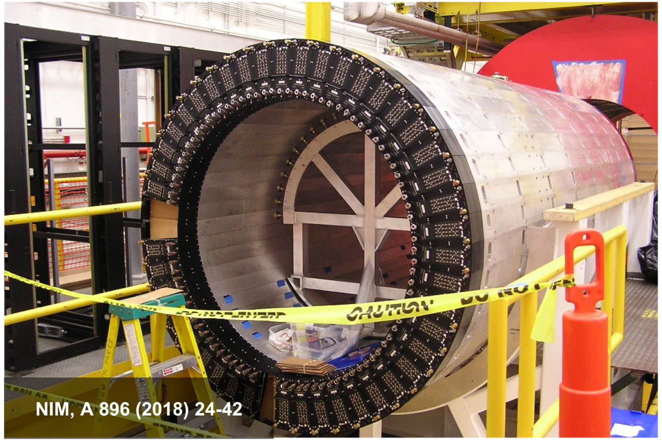
BIC x-Q² coverage



3

A Hybrid Imaging Calorimeter

Combination of a high-performance sampling calorimeter with silicon sensors for shower profiling


NIM, A 896 (2018) 24-42

NIM, A 1019 (2021) 165795

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

Insert layers of monolithic AstroPix sensors (ultra-low-power silicon sensor developed for NASA) in the first half of the calorimeter to capture a 3D image of the developing shower

4

Pb/ScFi Layer Technology

Our Pb/ScFi layers follow the GlueX Design

Energy resolution at GlueX: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$[1)]

- GlueX has 15.5 X_0, and could not constrain the constant term (due to low energies) → fixed in FTBF/CERN Beam Test (< 2%)

Position resolution in z: 1.1cm/√E [2)]

- 2-side SiPM readout, Δt measurement

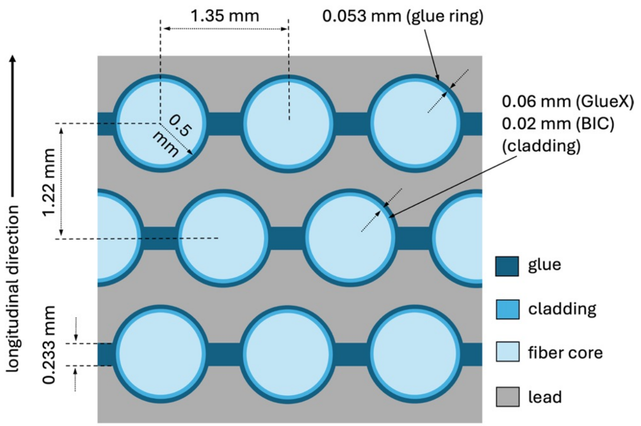
Mature technology used in Barrel ECals (GlueX, KLOE)

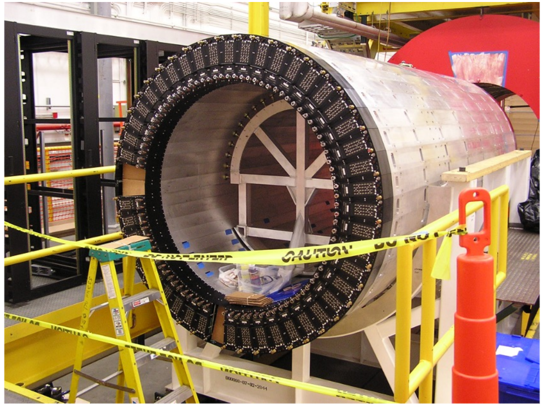
- Detailed studies on **calorimetry performance**, including the light collection uniformity in fibers, light collection efficiencies, etc.
- **Construction** (lead handling, swaging, Pb/ScFi layers assembly, module machining) is fully developed for GlueX

  Z. Papandreou, https://halldweb.jlab.org/DocDB/0031/003164/

Long-lead procurement items are ongoing for BIC (past FDR)

- SiPMs 1.2 x 1.2 mm^2 arrays, 50 um pitch (Hamamatsu S14160-6050-04 or similar)
- Single Clad Kuraray (SCSF-78, ø 1mm)





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

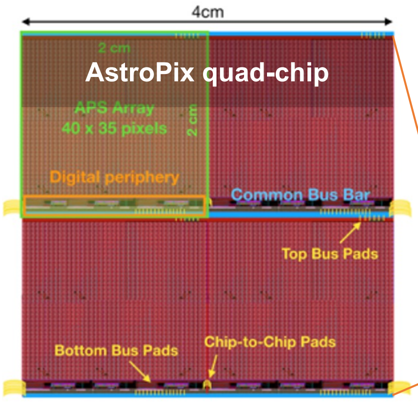
Imaging Layer Technology

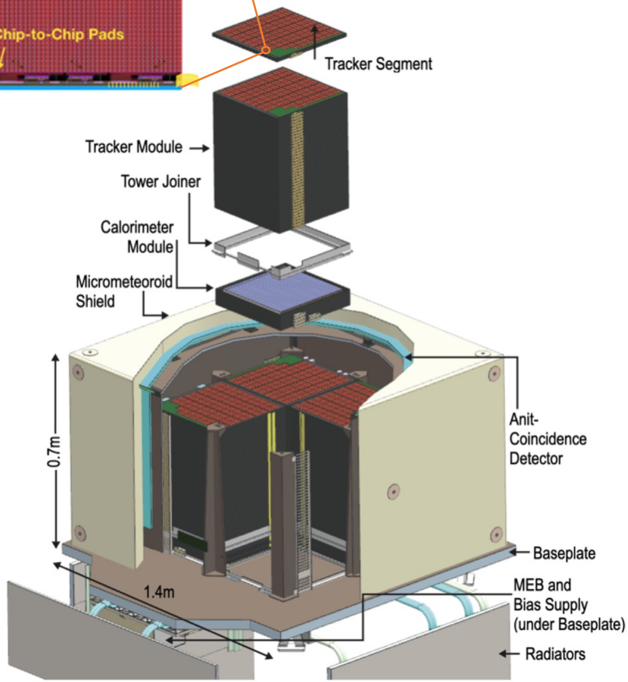
Imaging layers will use the AstroPix sensors

- Developed for NASA AMEGO-X space mission [arXiv:2109.13409](https://arxiv.org/abs/2109.13409) [astro-ph.IM]

Key features:

- Very low power dissipation - will be used in space!
- Good energy resolution (thick silicon sensor)
- 500 μm pixel size (~144 μm resolution)
- **Perfect for use in calorimetry!**
- First silicon layer has sufficient resolution to be used as a tracking layer behind the DIRC (replacing the MPGD layer)





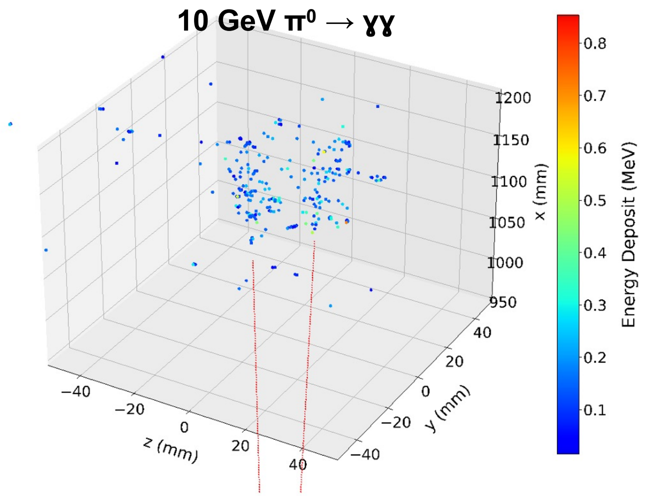
AMEGO-X Detector

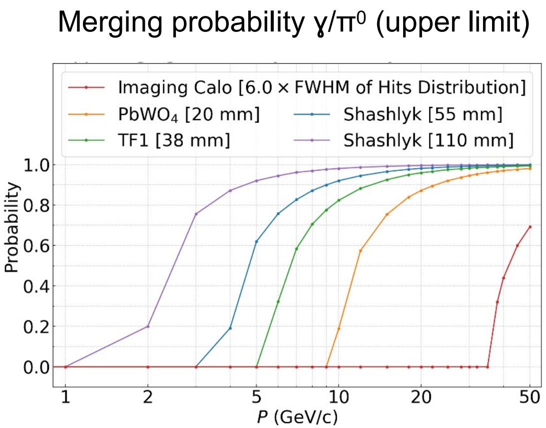
[arXiv:2208.04990 [astro-ph.IM]](https://arxiv.org/abs/2208.04990)

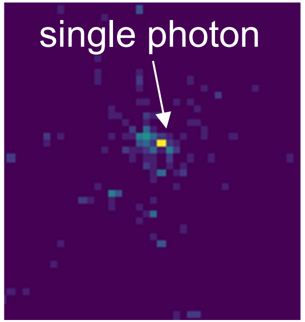
6

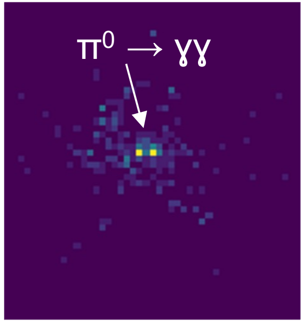
Particle Identification

Photons and Neutral Pions





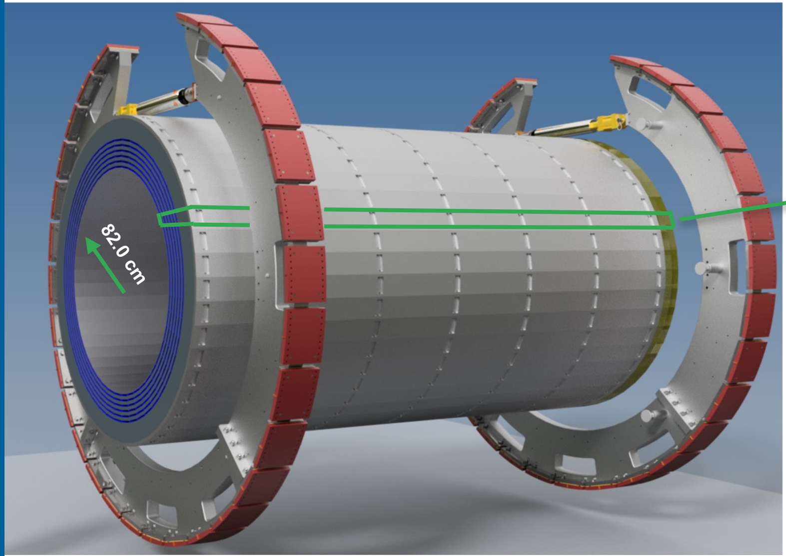




- Precise position resolution and shower imaging allow for excellent separation of γ/π^0 **based on the 3D shower profile**
- Upper limit unticipated from the **AstroPix position resolution and shower profile: well above 10 GeV**
- First insights from a simple **neural network approach** (**~82% pion rejection at 90% efficiency above 10 GeV** with the current status of model training - lower limit)

Barrel Imaging Calorimeter

Sector Mechanics

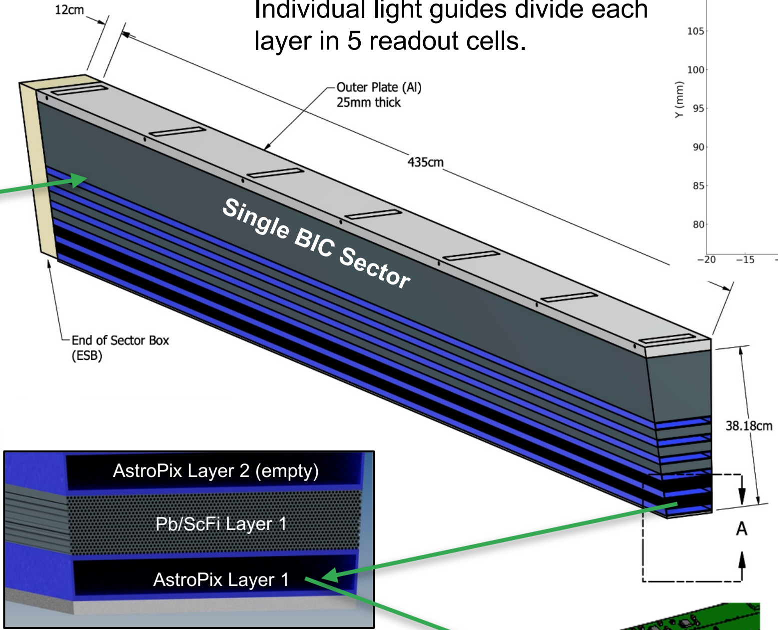


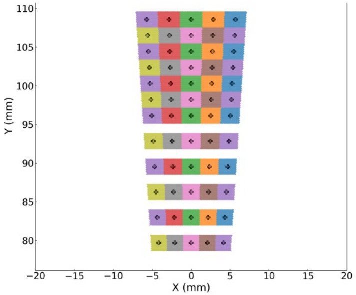
Total BIC weight ~42.5 US tons

Pb/SciFi Layers - 17 rows of fiber between corrugated lead.

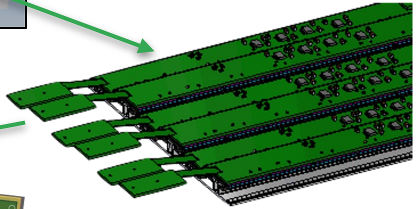
Each sector has 12 Pb/ScFi layers.

Individual light guides divide each layer in 5 readout cells.





SiPMs - 5 per layer x 12 layers = 60 (Hamamatsu S14161-3050)

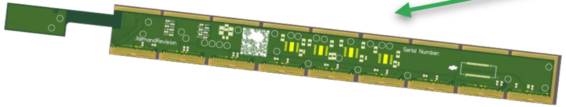


Tray - Structure holding the AstroPix staves for a single layer (217.5 cm long).

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

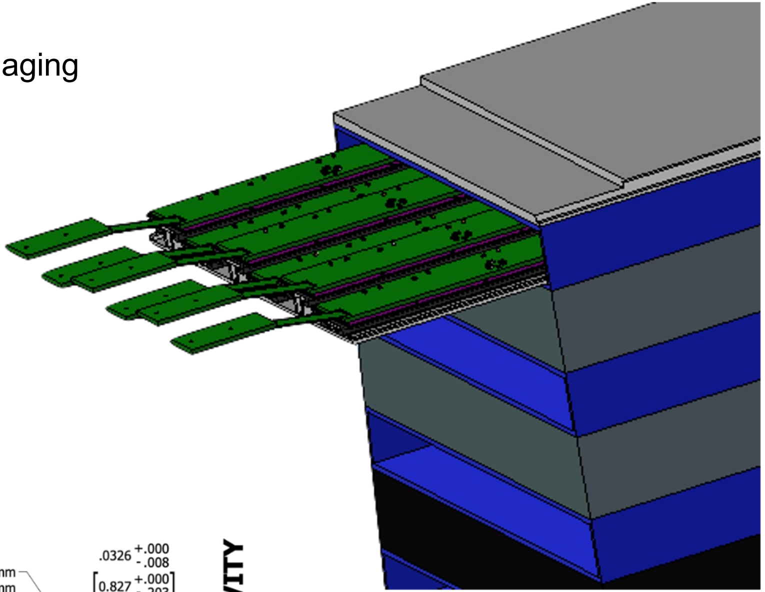
A stave consists of 12 modules.

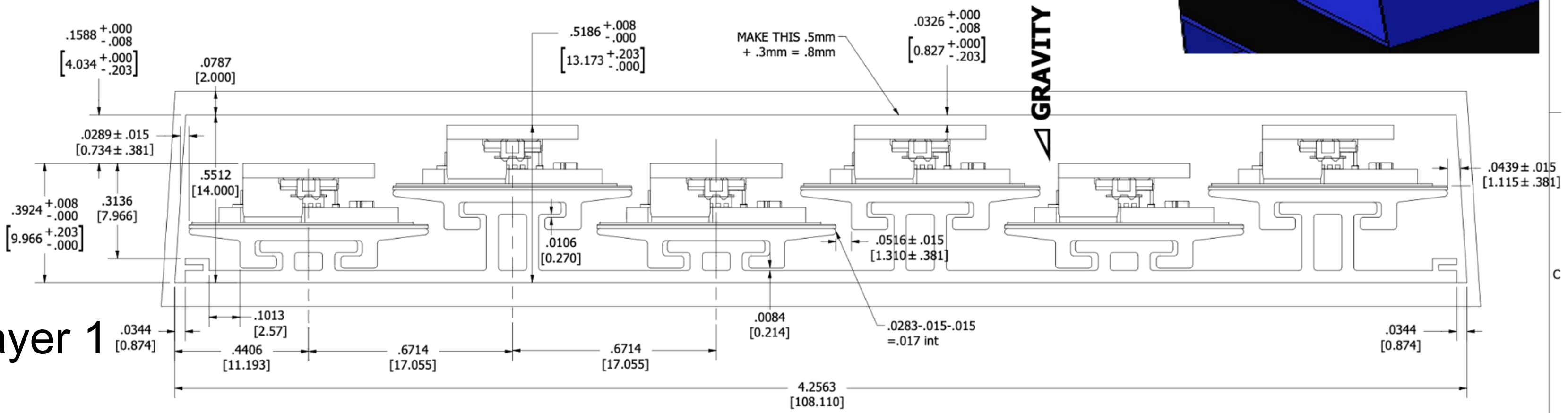
A tray contains of 6-8 staves.



BIC Imaging Layers

- **A Module** is an electrically testable elementary unit for imaging layers
    - **9 AstroPix HV-CMOS chips** - 2 cm ⨉ 2 cm
    - Base Plate (Aluminum) slides on Stave rail
    - Rigid(-flex) PCB readout
- 12 modules form a **Stave** and readout at the end of the Sector using End of Tray Card (FPGA) (~217cm)
- **Tray** consists of (6, 7, 7, 8) Staves (56 Staves/Sector)
- There are a total of 48 sectors with a length of ~435 cm
- The BIC is made up of 31104 Modules using ~280k chips





Layer 1

9

BIC Organization Chart

ePIC Leadership
Spokesperson:
- John Lajoie (ORNL)

Deputy Spokesperson and TC:
- Silvia Dalla Torre (INFN Trieste)

BIC DSC Board
DSC Leadership (DSL)
- Sylvester Joosten (Argonne)
- Hwidong Yoo (Yonsei U)
- Maria Żurek (Argonne)

Other Stakeholders
- Zisis Papandreou (U. Regina)
- Regina Caputo (NASA-GSFC)

BIC Project Manager
- Jessica Metcalfe (Argonne)

EIC Project L3 CAM
L3 CAM for Electromagnetic Calorimetry:
- Alexander Bazilevsky (BNL)

ePIC Technical Coordination
Technical Coordinator:
- Silvia Dalla Torre (INFN Trieste)

Deputy Technical Coordinators
- Prakhar Garg (Yale U.)
- Oskar Hartbrich (ORNL)
- Matt Posik (Temple U.)

BIC Project Management
Project Manager (and DSTC):
- Jessica Metcalfe (Argonne)

Deputy Project Manager
- Sylvester Joosten (Argonne)
- Maria Żurek (Argonne)

AstroPix Wafers / Modules & Staves
TM: Manoj Jadhav (Argonne)
Deputy TM: Sanghoon Lim (PNU)

Chip Support
PoC: Richard Leys
Sites:
- KIT
- NASA-GSFC

Wafer Testing
PoC: Sanghoon Lim
Sites:
- PNU
- Argonne

Wafer Procurement
PoC: Jessica Metcalfe
Sites:
- Argonne
- PNU

Module Design & Assembly
PoC:
- Manoj Jadhav
- Anthony Affolder
- Sanghoon Lim

Sites:
- Argonne
- UCSC
- PNU

Stave Bus
PoC: Steven Welch
Sites:
- Oklahoma State

Mechanics / Sectors
TM: Sylvester Joosten (Argonne)
Deputy TM: Beomkyu Kim (SKKU)

Global Design
PoC: Tom O'Connor
Sites:
- Argonne

Tracker Mechanics
PoC: Vic Guarino
Sites:
- Argonne

CF Engineering
PoC: Andreas Jung
Sites:
- Purdue

Assembly & Install.
PoC:
- Kevin Bailey
- Dan Cacace

Sites:
- Argonne
- BNL (EIC Project)
- ePIC BIC DSC

Sector Production
PoC:
- Kevin Bailey

Sites:
- Argonne
- SKKU
- Yonsei U.

Scintillating Fibers
PoC: Zisis Papandreou
Sites:
- U. Regina
- Argonne

ESB / DAQ & Readout
TM: Zisis Papandreou (U. Regina)
Deputy TM: Shinhyung Kim (KNU)

SiPMs & Light Guides
PoC: Zisis Papandreou
Sites:
- U. Regina
- KNU

Electrical Design
PoC: Aram Teymurazyan
Sites:
- U. Regina

Cooling
PoC: Wouter Deconinck
Sites:
- U. Manitoba
- Argonne

ESB Production
PoC:
- Zisis Papandreou
- Wouter Deconinck
- Shinhyung Kim

Sites:
- U. Regina
- U. Manitoba
- Mt. Allison U.
- KNU

ETC
PoC: Regina Caputo
Sites:
- NASA-GSFC

SiPM FEB & DAQ Integration
PoC: Norbert Novitzky
Sites:
- ORNL
- U. Regina
- U. Manitoba

Slow Controls
PoC: TBD
Sites:
- Argonne
- ORNL
- PNU

System Testing / Software & Sim
TM: Maria Żurek (Argonne)
Deputy TM: Hwidong Yoo (Yonsei U.)

System Demonstration
PoC: Henry Klest
Sites:
- Argonne
- U. Regina
- PNU

Beam Tests
PoC: Bobae Kim
Sites:
- Argonne
- U. Regina
- EIC Korea

System Calibrations
TBD

System QC
PoC: Maria Żurek
Sites:
- Argonne
- U. Regina
- BNL (EIC Project)

Rapid Response
PoC: Maria Żurek
Sites:
- Argonne
- U. Manitoba
- PNU

Development
PoC: Chao Peng
Sites:
- Argonne
- U. Manitoba
- U. Regina
- PNU

Benchmarks
PoC: TBD
Sites:
- Argonne
- U. Manitoba
- PNU

Glossary
BIC: Barrel Imaging Calorimeter
CAM: Control Account Manager
DSC: Detector Subsystem Collaboration
DSL: Detector Subsystem Lead
DSTC: Detector Subsystem Technical Contact
ESB: End-of-Sector Box
ETC: End-of-Tray Card (AstroPix module RDO)
FEB: Front-End Board
PoC: Point-of-Contact
PM: Project Manager
QC: Quality Control
RDO: Readout board
TBC: To Be Confirmed
TBD: To Be Determined
TM: Technical Manager

BIC ORG Chart v1.0

***Note:** The BIC internal work packages (AstroPix Wafers, Modules & Staves, Mechanics, Sectors, ESB, DAQ & Readout, and System Testing) are integrated under the EIC Project P6 Work Packages*

BIC Project Phases

PED: Preliminary Design → PED: Final Design → Preproduction → Production

- Preliminary Design Review
  Sept 2026
- Final Design Review
  Spring/Summer 2026
- Need CD3 approval to start production articles
  2027/2028 Production Readiness Review
- Ready for installation
  ~Dec 2031

PED: Preliminary Design

- Preliminary Design Review, 60% design completion
- AstroPix v3 (and v4)
- BabyBCal & Lanky BCal
- Individual components
- First (second) test articles

PED: Final Design / Preproduction

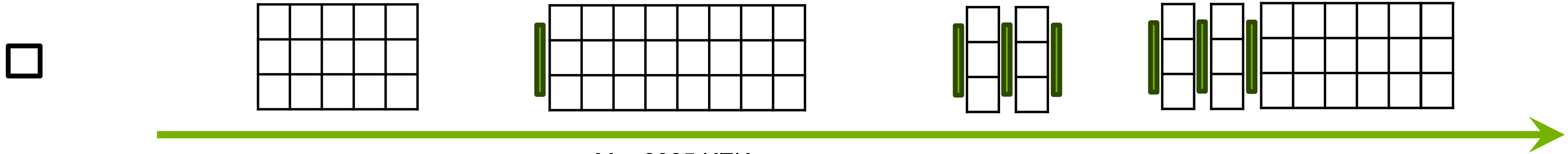
- AstroPix v5
- One full sector
- Final designs (90%)
- Production style procedures
- AstroPix v6 validation tests

Production

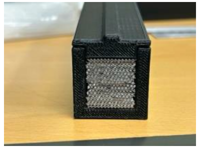
- AstroPix v6
- 48 sectors

11

Beam tests of the prototype detector

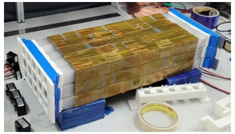


May 2024



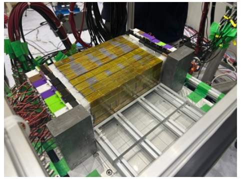
First piece

Aug 2024 CERN PS



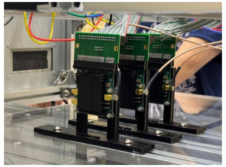
First Pb/SciFi prototype production in Korea
First beam test
Successful data taking

Mar 2025 KEK



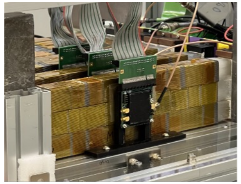
More Pb/SciFi layers
Improved energy resolution
New DAQ, Trigger, Hodoscope, Calibration
Extension cable test

June 2025 KEK



AstroPix synchronization with trigger time

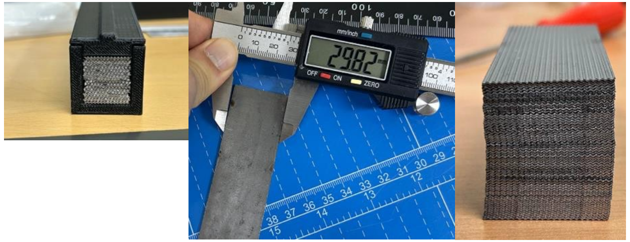
July 2025



synchronized data taking of AstroPix + Pb/SciFi
Proof-of-principle imaging of electrons and pions
Resolution fulfill the EIC requirement

Pb/SciFi Prototype Module Production

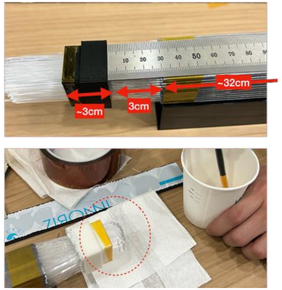
1) Pb plate preparation



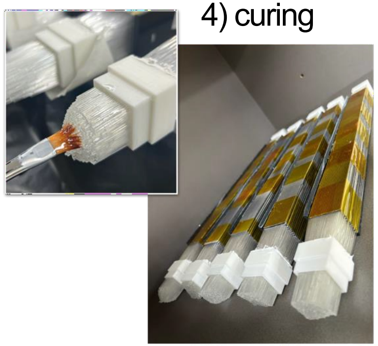
2) Stacking with fiber

Epoxy

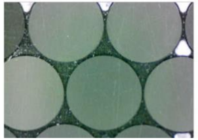
3) Cutting fiber



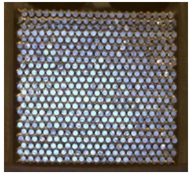
4) curing

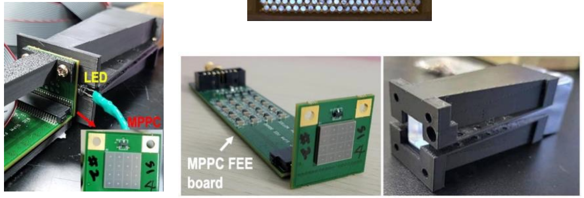


5) polishing

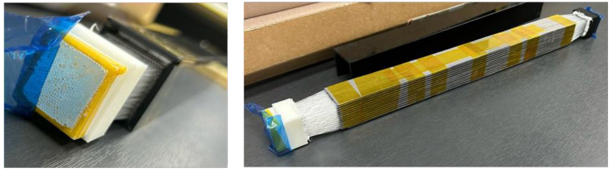


Produced 33 of 32x3x3 cm^3 unit modules for beam test



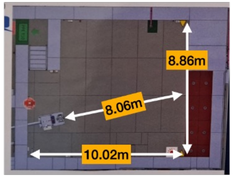


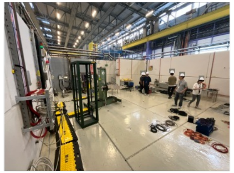
완성본

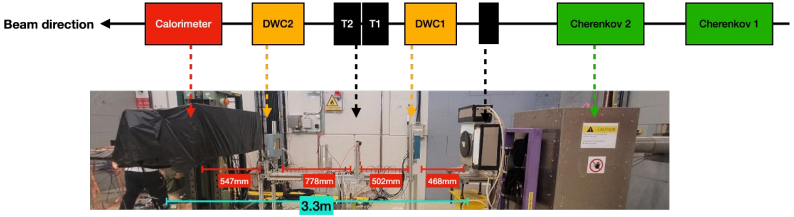


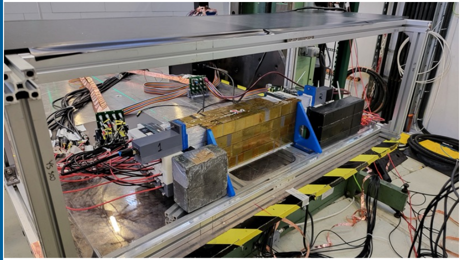
6) Connect with PMT or Light Guide + SiPM

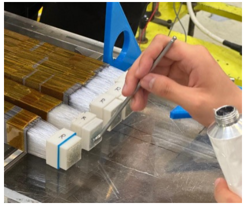
First beam test at CERN PS T10 in Aug 2024

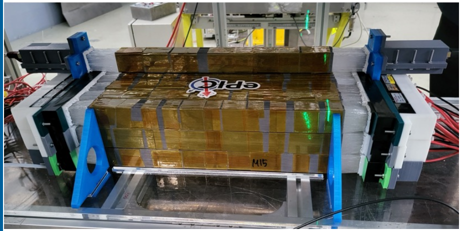


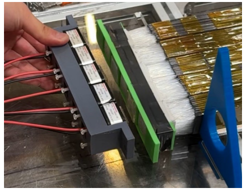


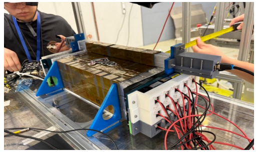


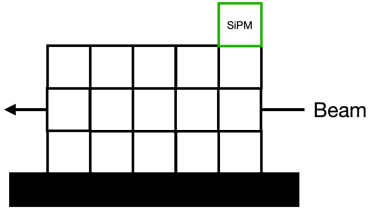


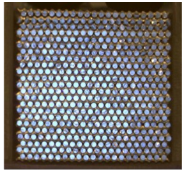




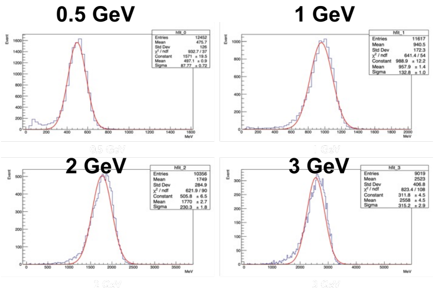




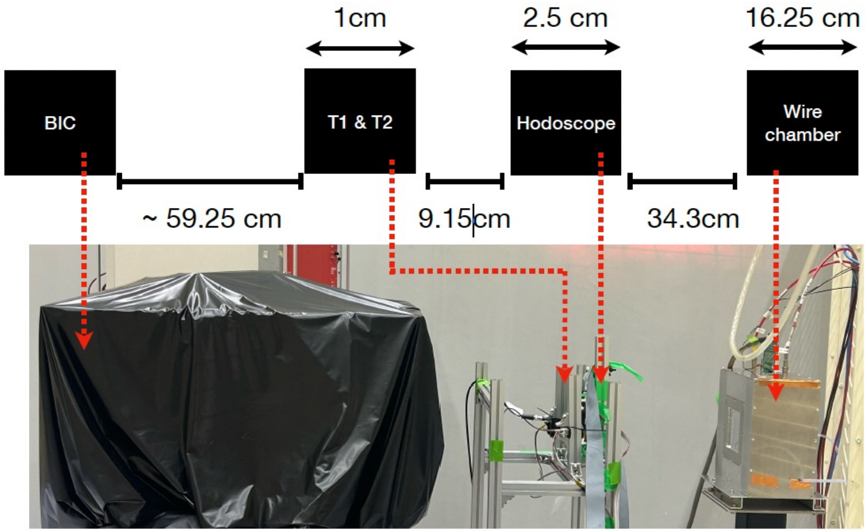


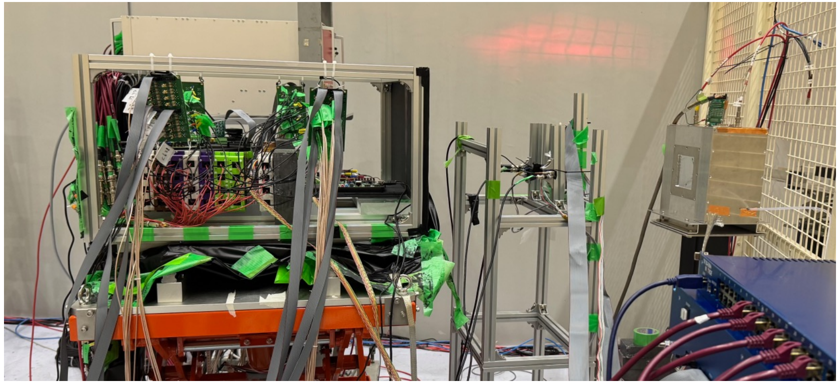


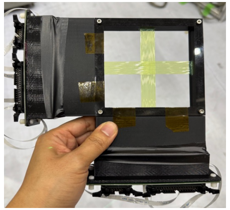
Successfully collected data from the Pb/SciFi calorimeter prototype produced in Korea using our DAQ system with 0.5, 1, 2, and 3 GeV electron beams.

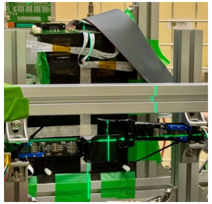


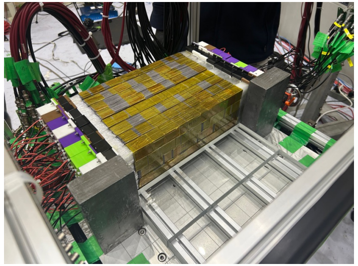
Second beam test at KEK PF-AR in Mar 2025









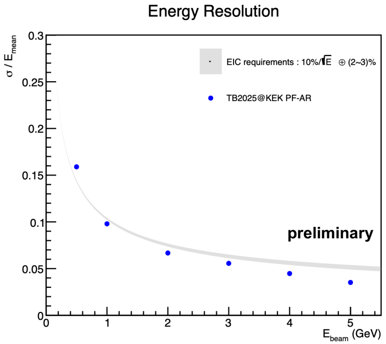


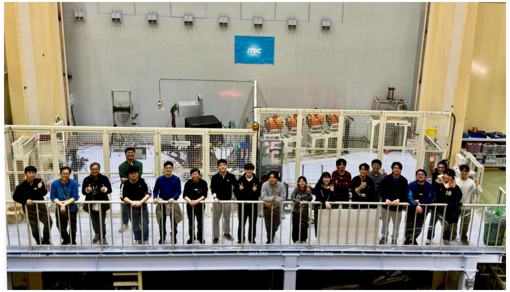
Bigger, Deeper Pb/SciFi setup: 32x12x21cm³

Refine calibration procedure

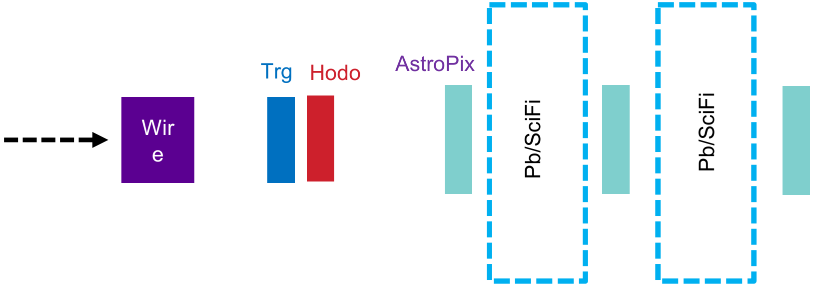
Smooth operation with new DAQ

Operation of auxiliary detectors: Hodoscope, Trigger

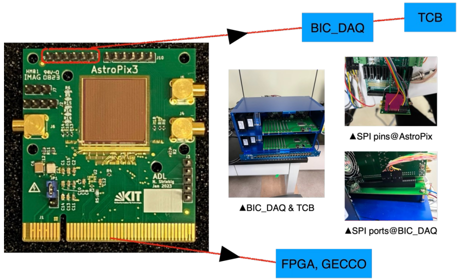


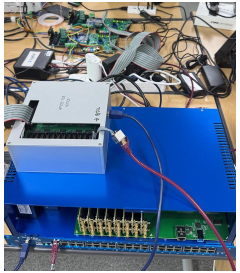


Third beam test at KEK PF-AR in June 2025



3 AstroPix Layers to be synchronized

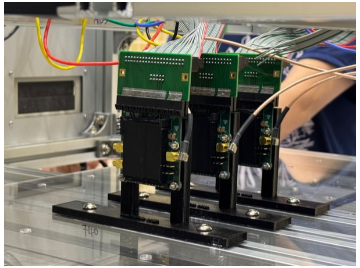


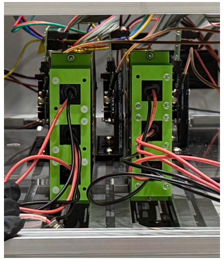


Synchronization between AstroPix and other detectors in the DAQ system produced in Korea

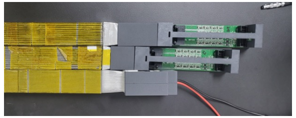
Preparation of the shower profile study.

SiPM and Light Guide test

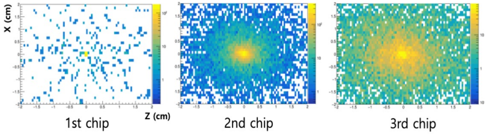




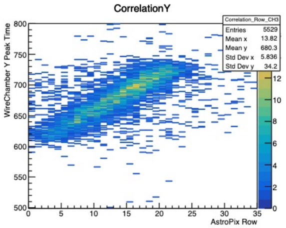
3 AstroPix Layers between Pb/SciFi



S13,S14 SiPM with LG

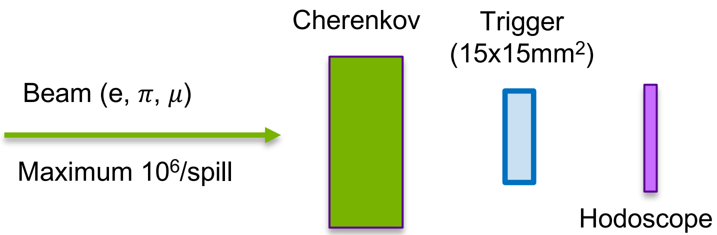


Hit distribution from electron beam in GEANT4 simulation

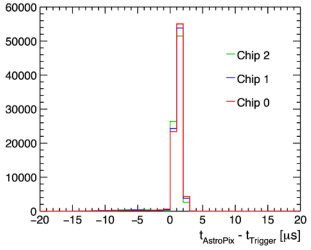


correlation of beam position at AstroPix and drift time at Wire Chamber

Recent beam test at CERN PS T10 in July 2025

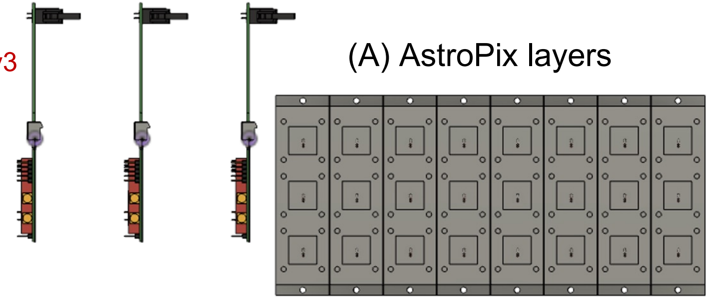


Time between
AstroPix and Trigger

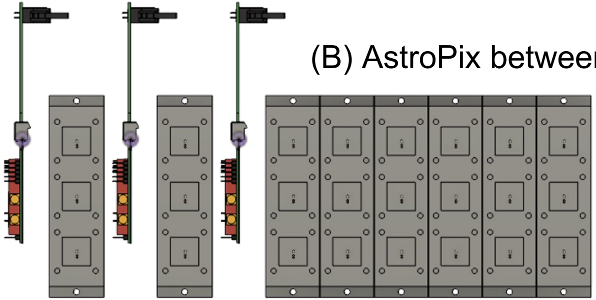


AstroPix v3

(A) AstroPix layers



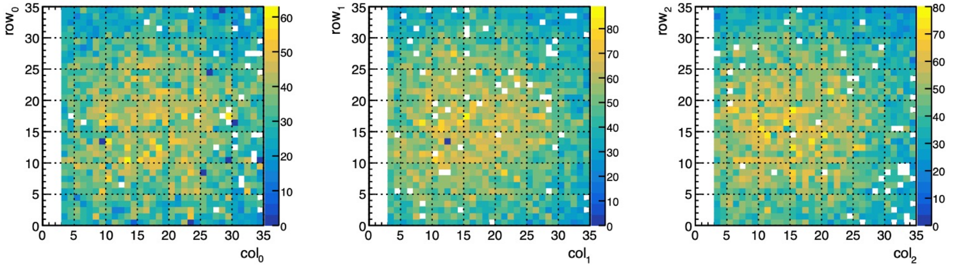
(B) AstroPix between Pb/SciFi



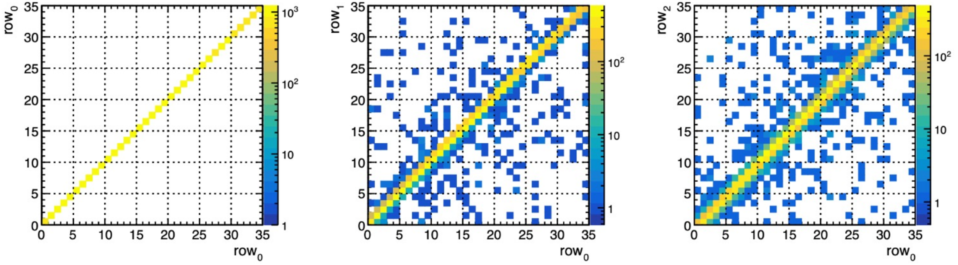
Goal: Proof-of-principle imaging of electrons and pions using a synchronized setup of AstroPix in the beam environment, using synchronized data taking between AstroPix and Pb/SciFi

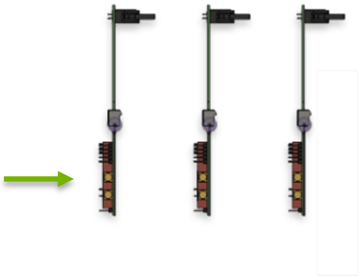
Synchronization of three layers of AstroPix v3

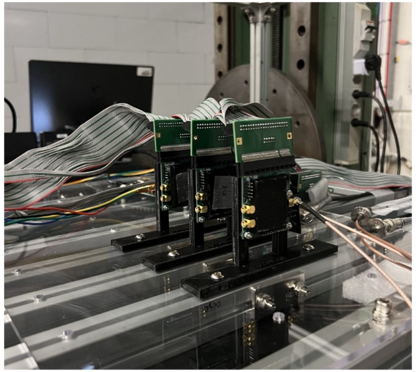
Hitmap



Correlation to the upstream chip

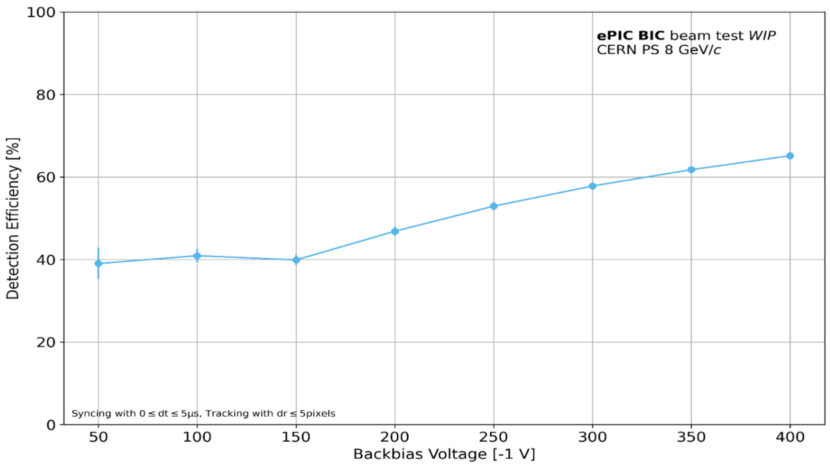


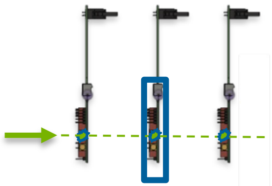


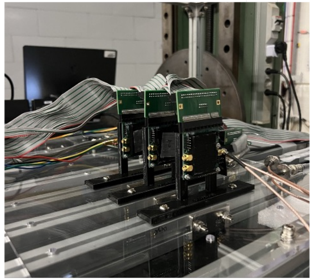


- Three AstroPix v3 layers are tested using the electron/pion beam at CERN PS.
- Correlations to the upstream show good alignment and data synchronization between AstroPix.
- The integrated system works well at a 2.7 kHz trigger rate on the beam. (BIC rate < 1 kHz/chip)

AstroPix v3 chip tracking efficiency (Shallow depletion depth)





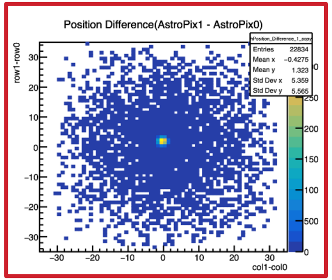


Detection efficiency in percentage as a function of bias voltage

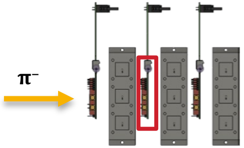
- Proof-of-principle for a method to measure tracking efficiency of AstroPix v3 under beam conditions.
- It is calculated as the probability of having a hit on the position estimated from hits on the first & third chips.
- The shallow depletion of v3 was known and is addressed in v5 with increased depletion.

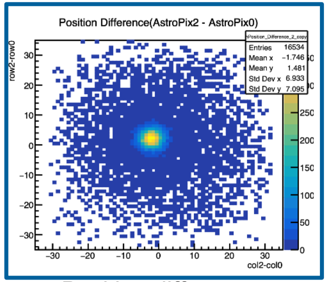
Different shower profiles of electrons and pions

Pions

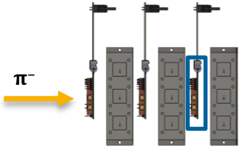


Position difference
between 1st-2nd layer

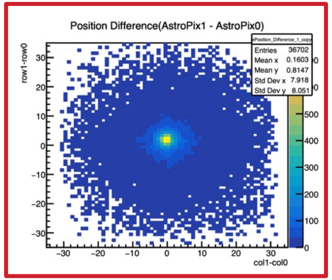




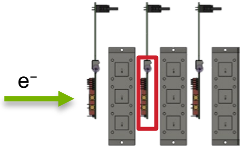
Position difference
between 1st-3rd layer

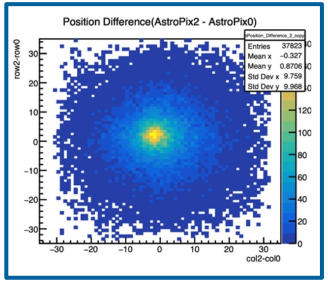


Electrons

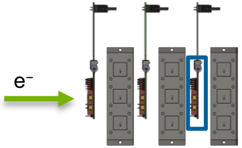


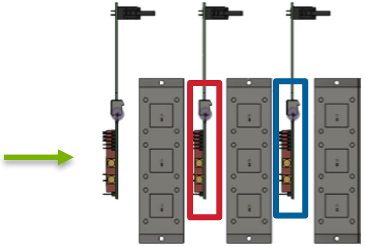
Position difference
between 1st-2nd layer

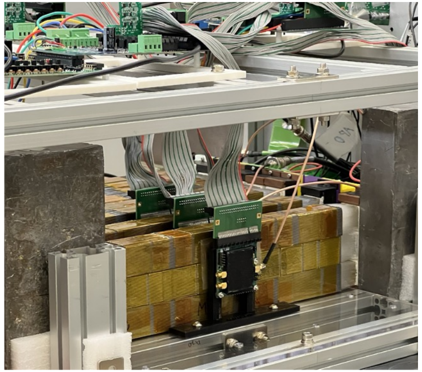




Position difference
between 1st-3rd layer

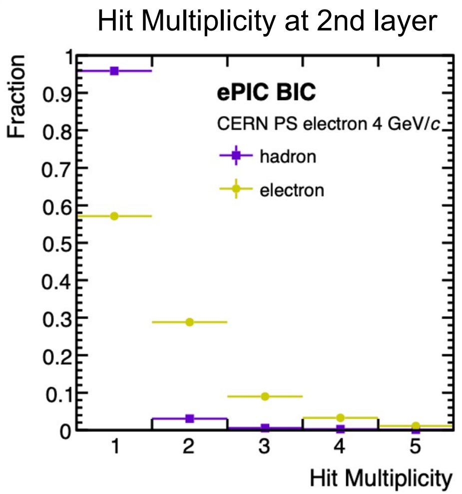


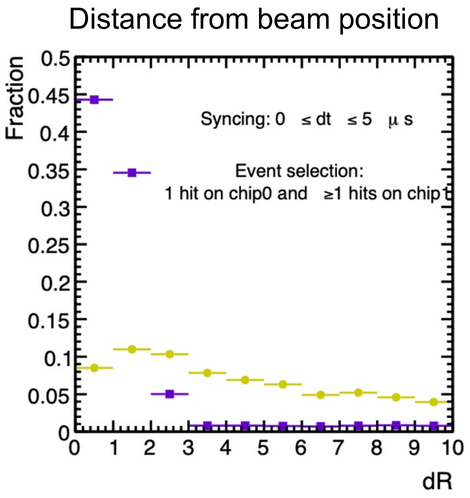


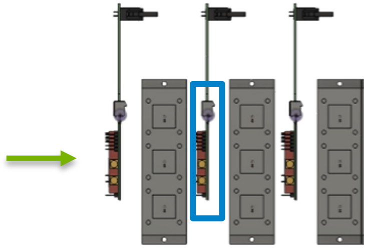


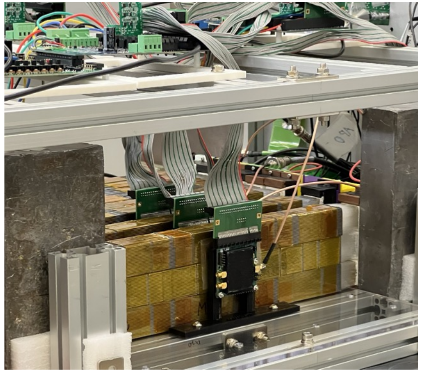
Proof-of-principle imaging of electrons and pions was performed using a synchronized AstroPix setup in the beam environment.

Different shower profiles of electrons and pions



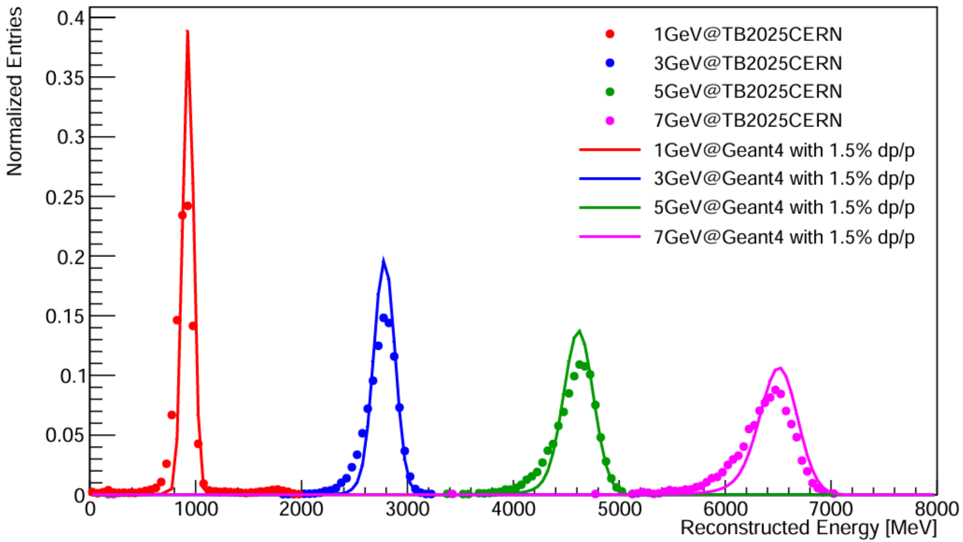






- The hit multiplicity and distance from the beam position at the second AstroPix v3 chip differ for electrons and pions.
- The electron/pion separation power in the beam test condition will be enhanced by AstroPix information on shower shape.

Electron energy measurement



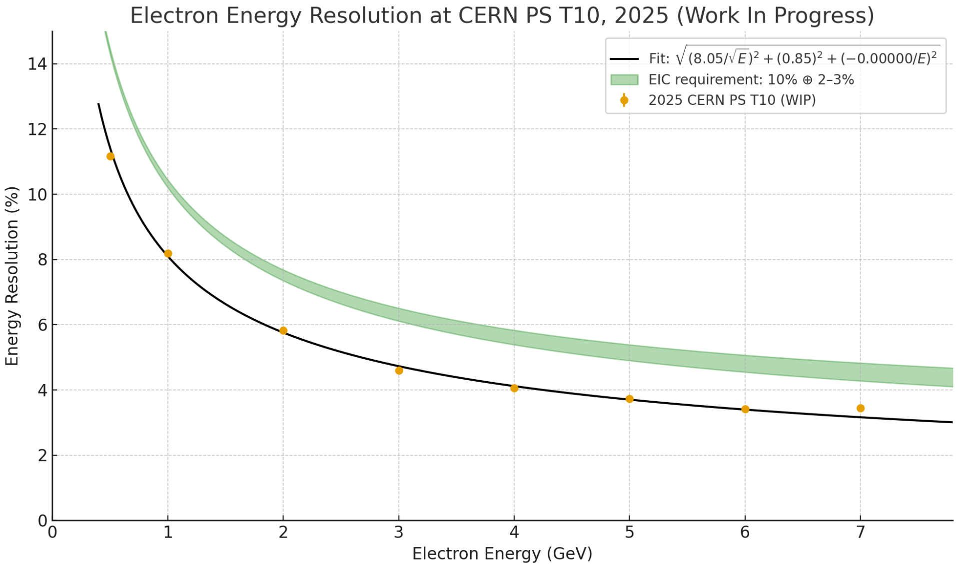
Applying beam momentum spread (dp/p) to simulation

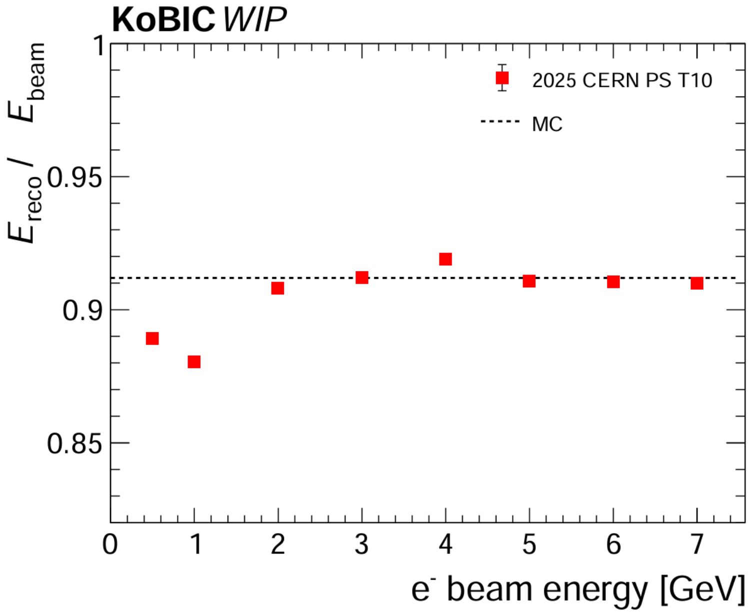
$$\sigma_{\text{total}} = \sqrt{\sigma^2_{\text{original}} + \sigma^2_{\text{spread}}}$$

***1.5% dp/p :** Expected momentum spread for the 3 mm collimator setup

- According to the GEANT4 simulation, energy resolution is affected by the beam momentum spread.
- At CERN PS T10, the beam momentum spread is 0.6~15%, depending on the collimator setup. (arXiv:2507.02567)
- With an additional momentum spread of 1.5%, the resolution in the simulation is shown with the data.

Energy Resolution & Linearity





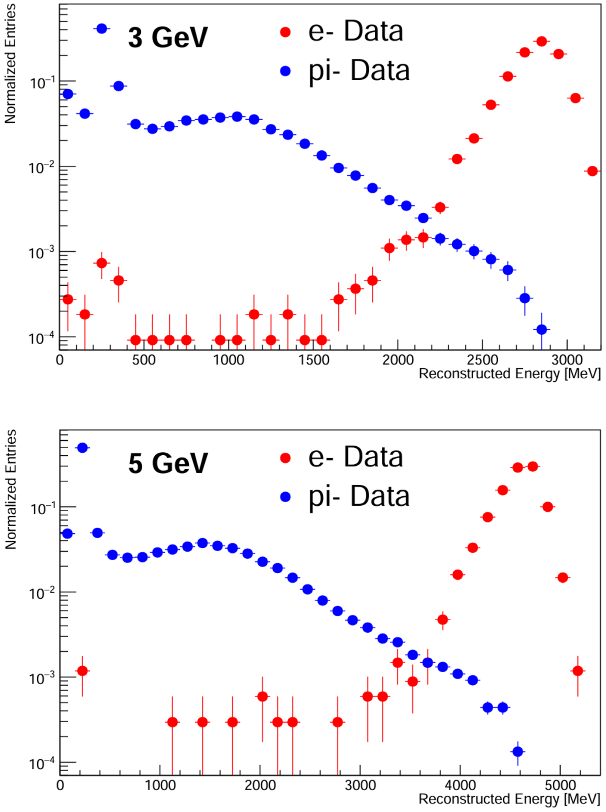
Resolution : (Stochastic) 8.05 %, (Constant) 0.85 %, (Noise) 0.00 %

$$\boxed{\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus c/E}$$

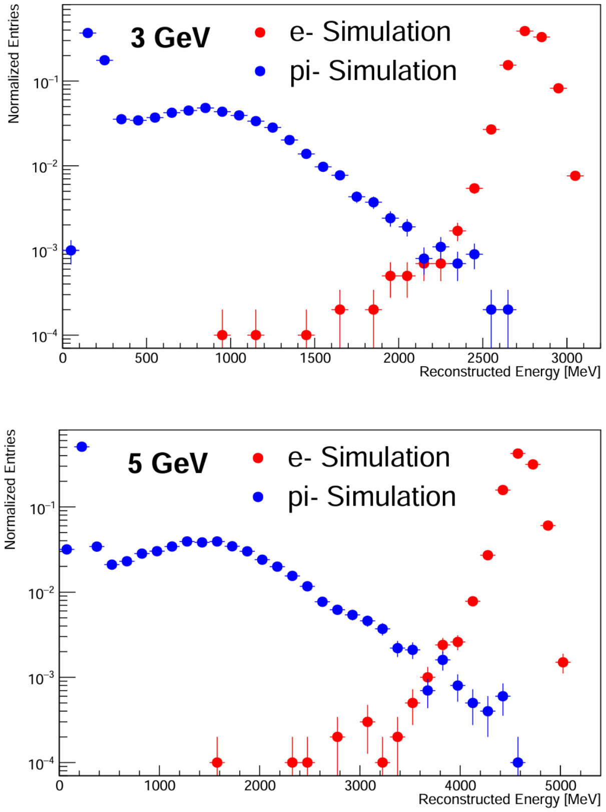
- The energy resolution has been progressively improved, achieving the best performance in this beam test.

e^-/π^- Separation in Beam Test Data

<Data> (Log scale y)

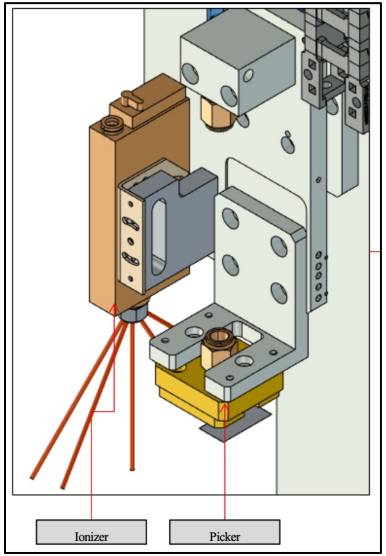


<Simulation> (Log scale y)

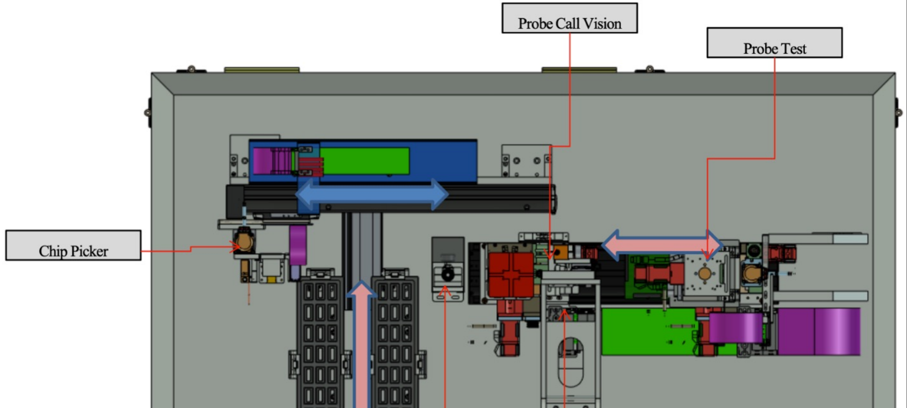


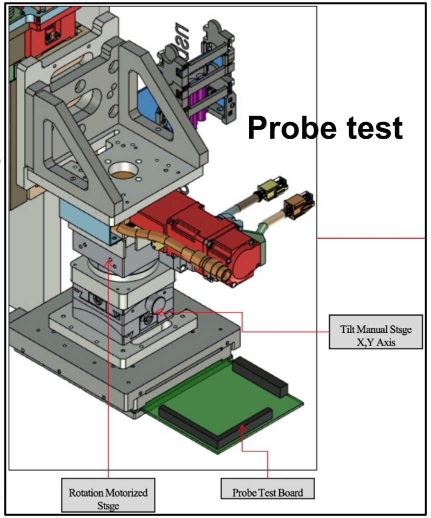
- Separating pions from electrons in data using a Cherenkov counter.
- Electron and pion energy distributions in data and simulation show good agreement.
- E/p allows discrimination between electrons and pions entering the calorimeter.

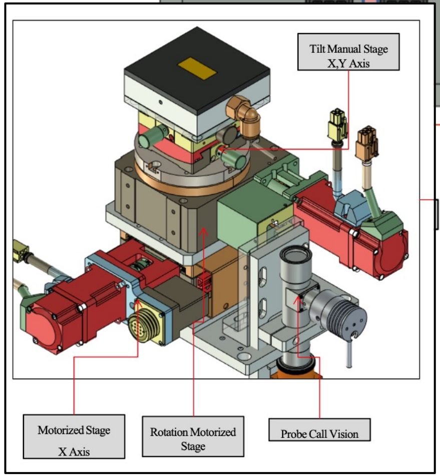
AstroPix test system



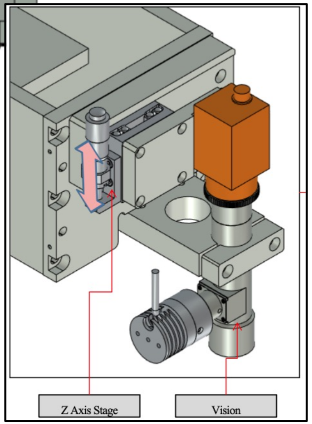
Sensor picker







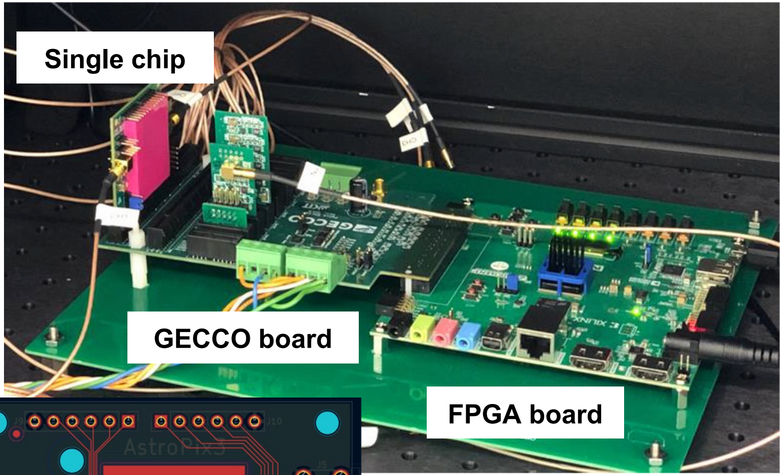
Working stage

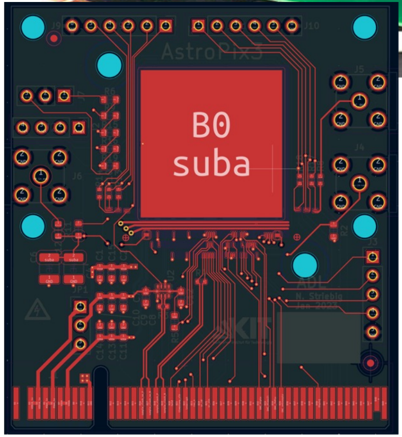


Vision inspection

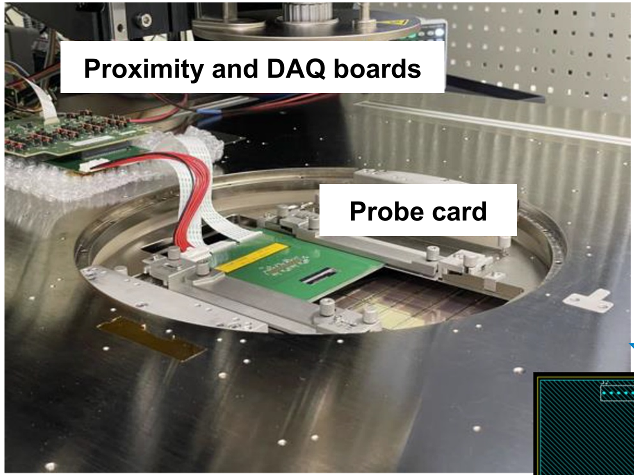
AstroPix test system

AstroPix v3 lab measurement setup

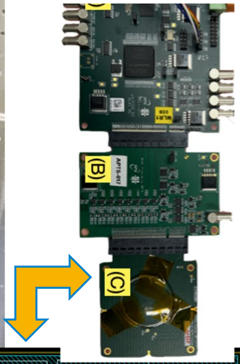


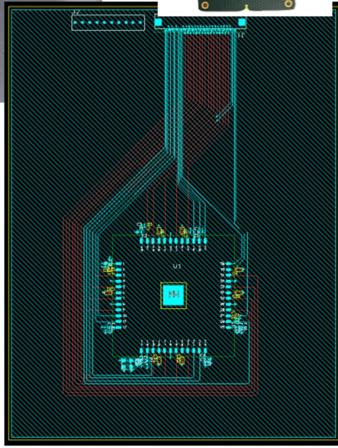


ALICE ITS3 ER1 wafer probing system



Testbench



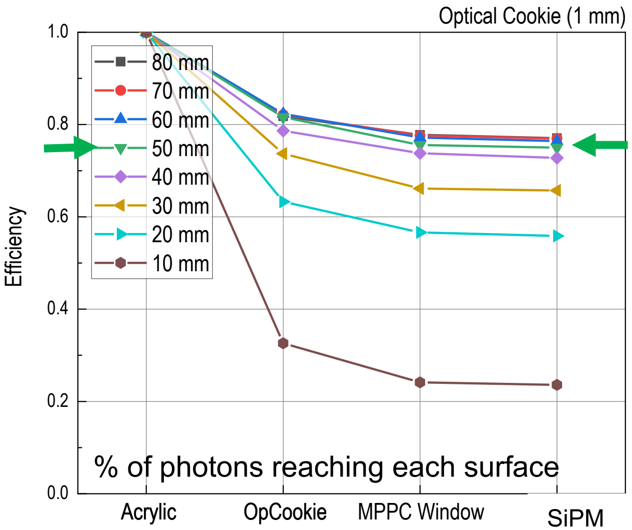


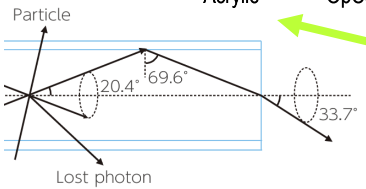
- Initial version of probe card for AstroPix v3: a simple version for the chip carrier board.
- Uses already validated GECCO and FPGA board setup, which will be connected with flexible cables
- Recently, the probe card design for v3 has been done by a local manufacturer in Korea

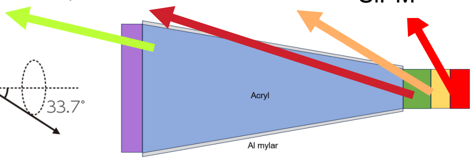
26

Development of the readout system

Transmission efficiency with LG length

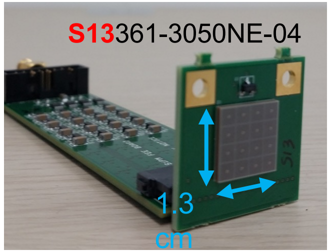


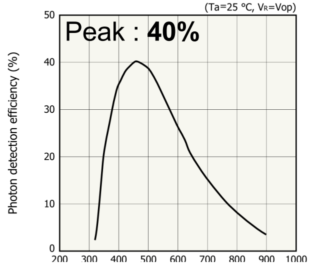


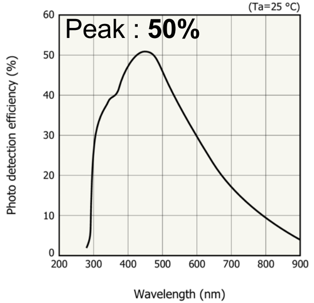


Optical simulation with random photon generation (ϕ < 20.4°)
Efficiency drops rapidly with lightguide length **under 5 cm.**

Silicon Photomultiplier



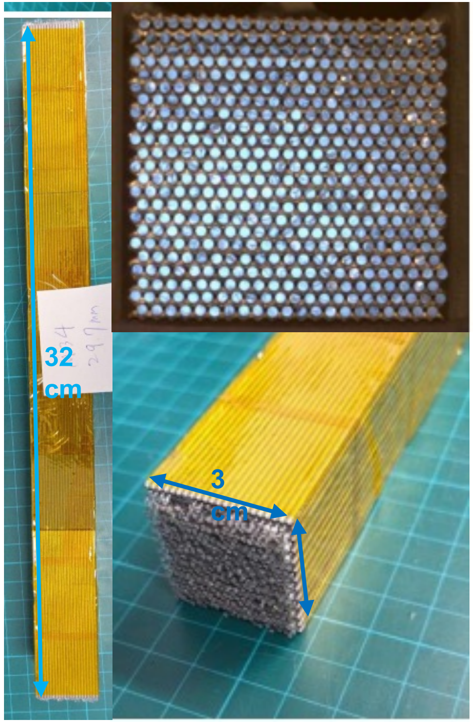


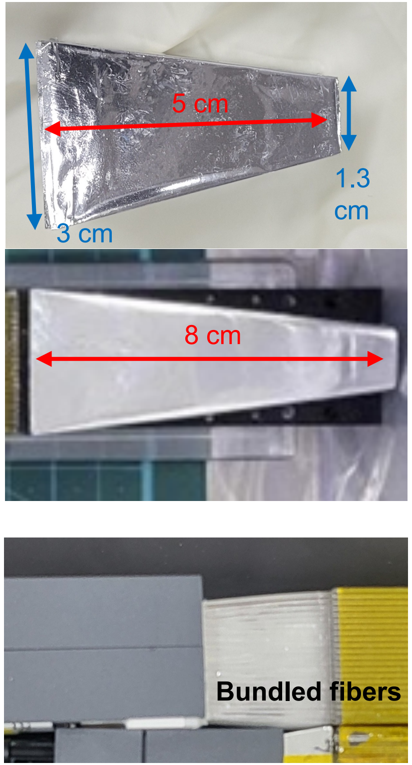


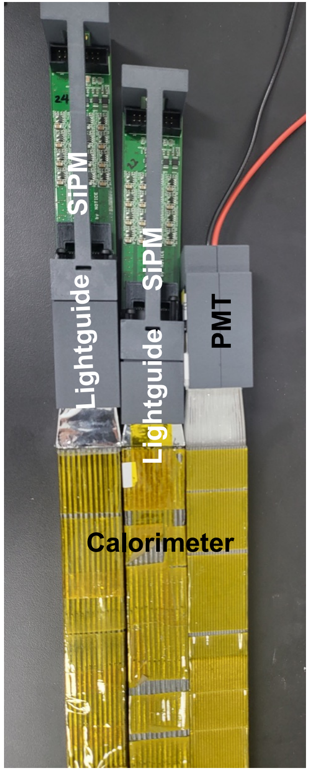
SiPM (S13 & S14, Hamamatsu)
Photon detection efficiency (S14 > S13)
Dark count rate (S14 > S13)
Neutron radiation hardness (S13 > S14)

27

Development of the readout system







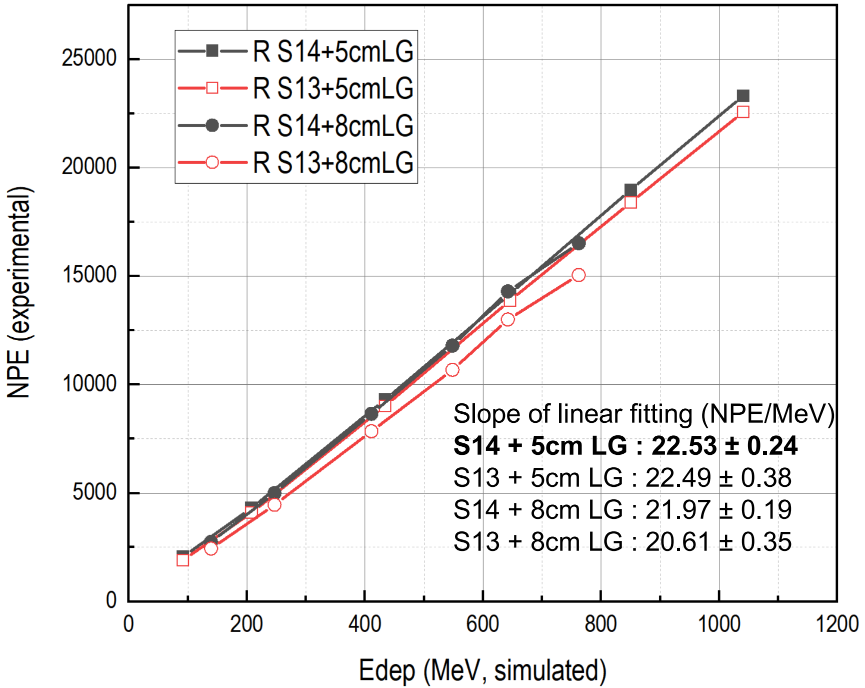
1. Calorimeter
Pb plates & Scintillating fibers

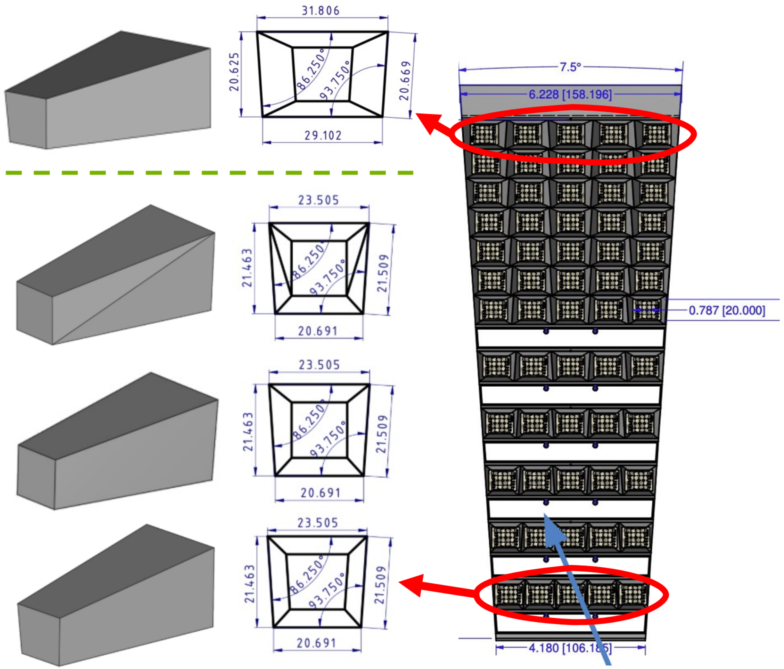
2. Lightguide
Square, acrylic lightguides wrapped with Al Mylar (5, 8 cm)
Bundled fiber for PMT

3. Photon senser (Hamamatsu)
SiPM (S13 & S14)
PMT

28

Development of the readout system

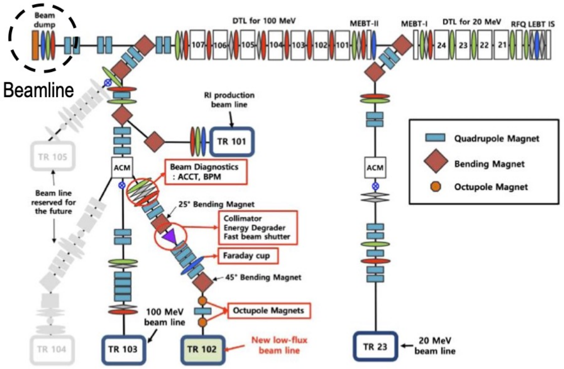


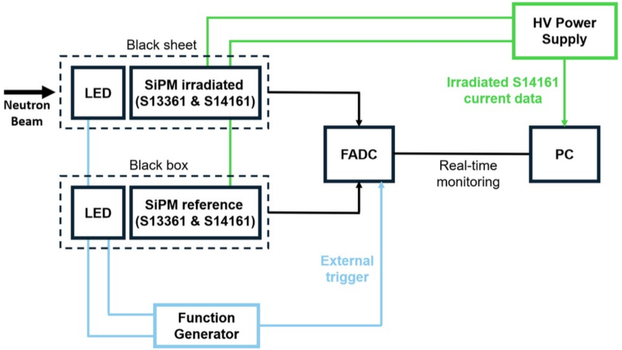


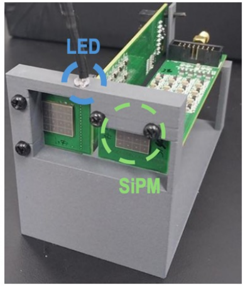
Beam test results
1. Linearity of SiPM readout
2. Small difference in light yield for SiPM readout (< 10%)

Future plan
Lightguides matching the dimensions for actual deployment will be tested

SiPM radiation hardness test







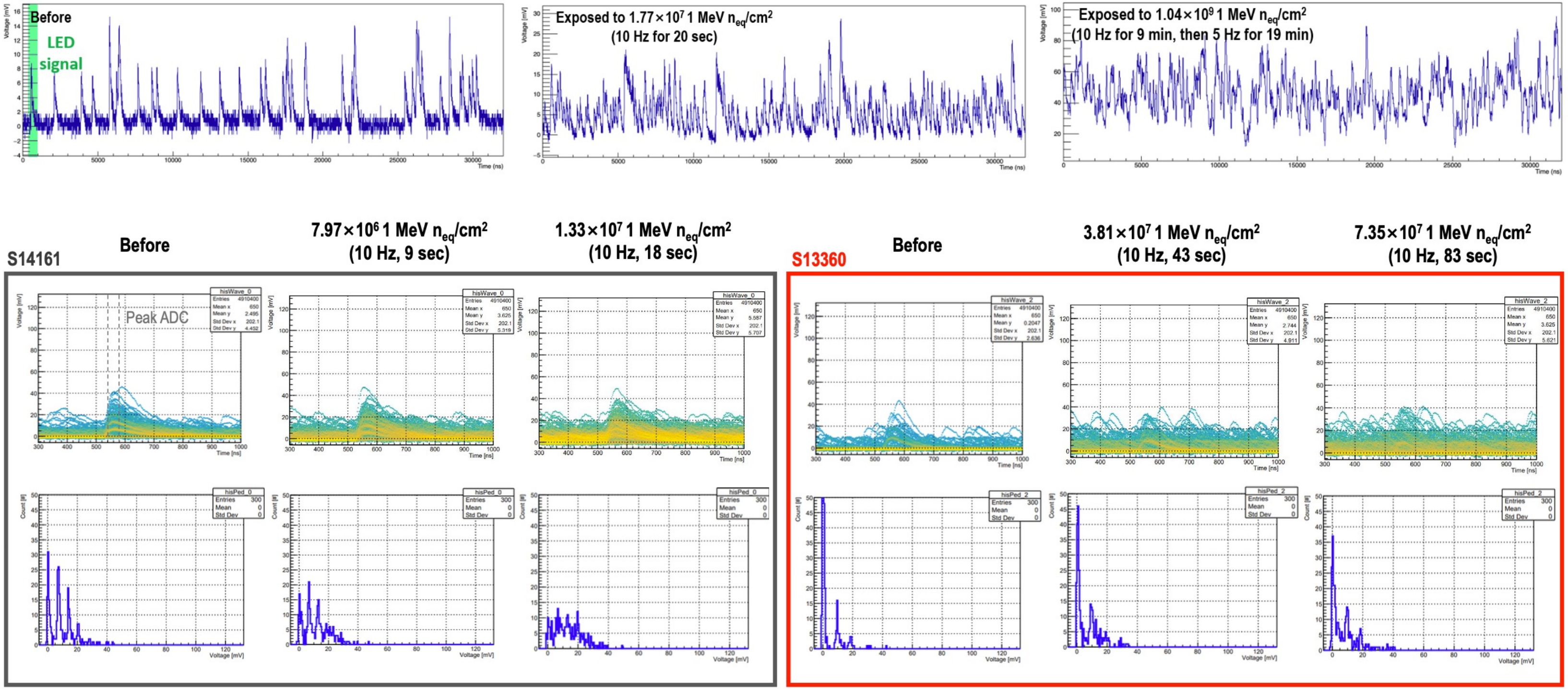
Date	Beam setting	Fluence [1MeV n_{eq}/cm^2]	LED Hz	Remarks
Jun 26	10 Hz × 5 min 10 Hz × 4 min 5 Hz × 19 min	1.04×10^9	100 Hz	Comparison of S13 and S14 S14: higher photon detection efficiency S13: lower dark count rate
Sep 5	1 Hz × 60 min vs 5 Hz × 12 min	6.20×10^8 (each)	100 Hz vs 500 Hz	Two pairs (S14 & S13) Same fluence, test for rate dependence

- Real-time SiPM irradiation monitoring: Two SiPMs (Hamamatsu S13361 and S14161) were irradiated with neutron beams at KOMAC, and monitoring of single-photoelectron response (LED window), dark current rate, and baseline shifts.

- Performance change evaluation: Pre- and post-irradiation IV measurements were performed to quantify leakage-current increases and breakdown-voltage shifts for both devices.

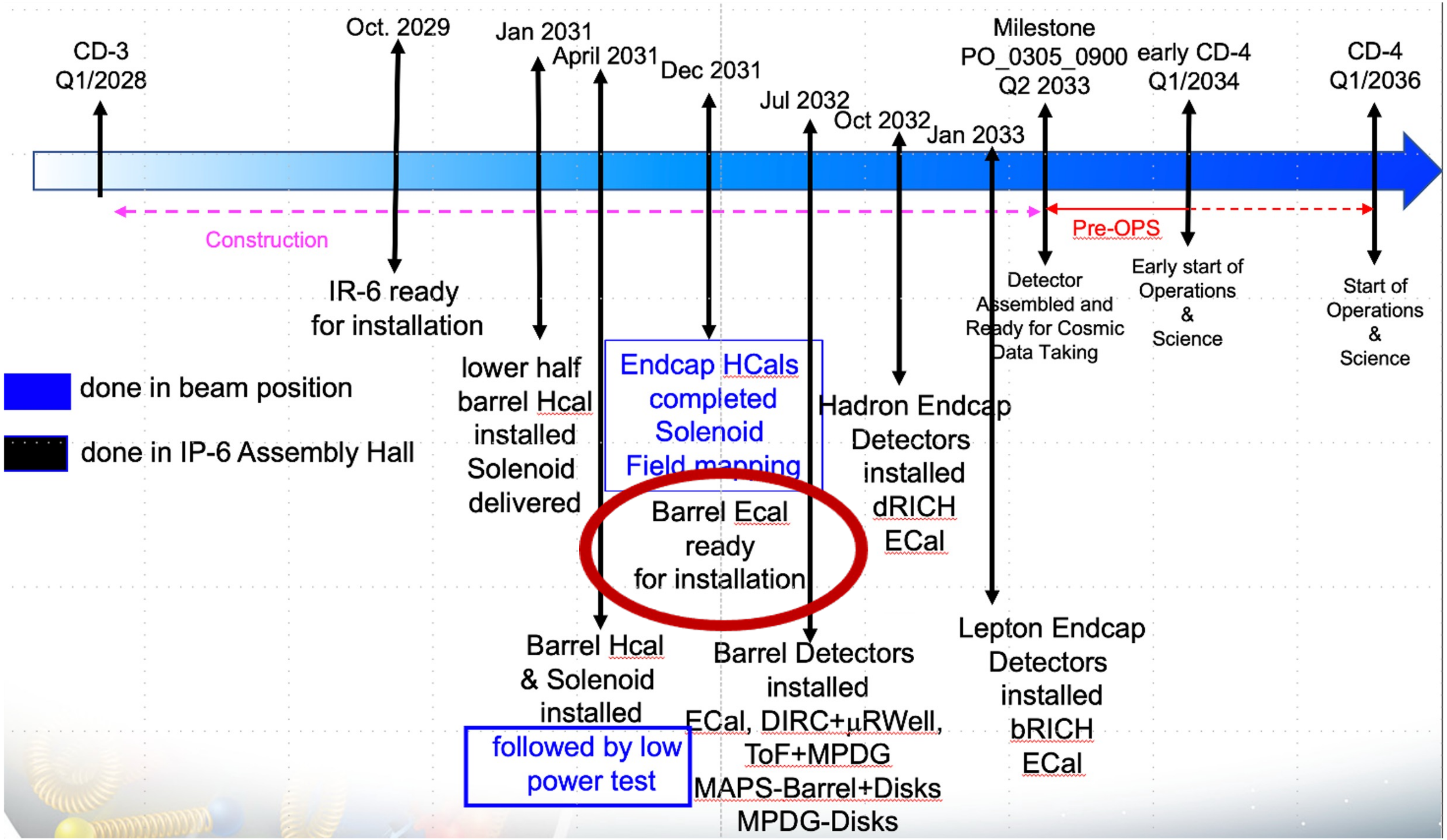
30

SiPM radiation hardness test



S14161 shows a lower ADC sigma as a noise indicator, while S13361 exhibits lower leakage current and better single-photoelectron peak separation during irradiation.

ePIC Schedule



Backup

AstroPix v5 Specifications

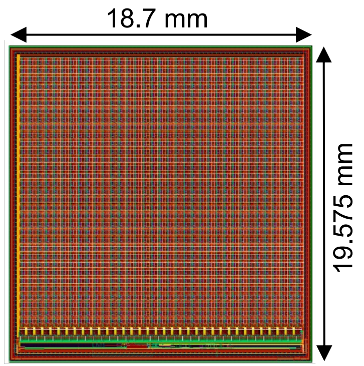
Pixel Matrix:

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 (2 columns)

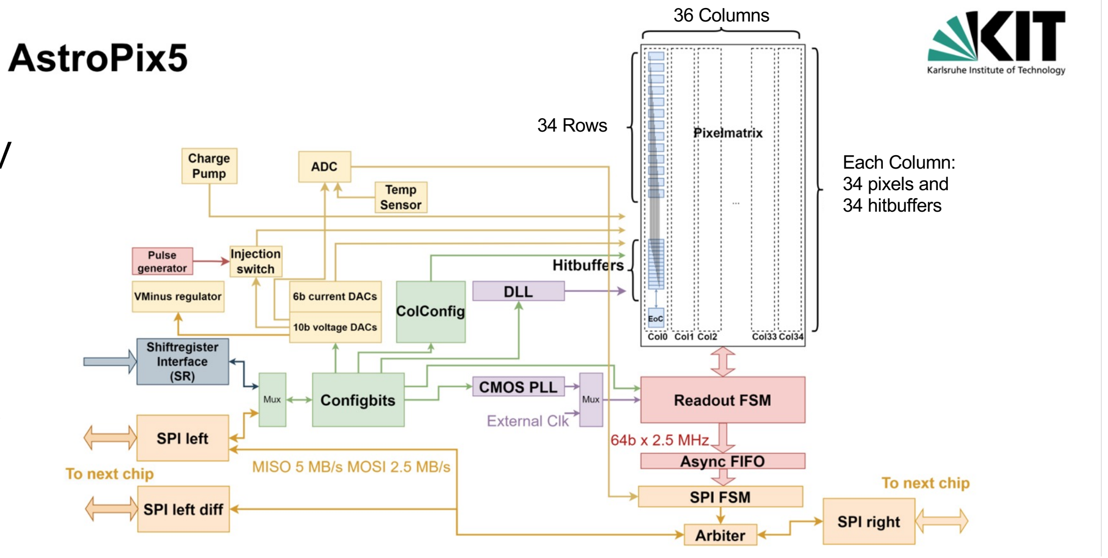
Power Consumption:

Pixel 4.6 uW
Pixel matrix 5.3 mW
Digital 2.2 mW
— 700 uW DigitalTop

Total: ~2 mW/cm^2



18.7 mm × 19.575 mm chip



Relevant AstroPix v6 Specifications

Pixel Matrix:

39 cols x 37 rows

—35 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 (decision from v5 validation)

Power Consumption:

Pixel 4.6 uW

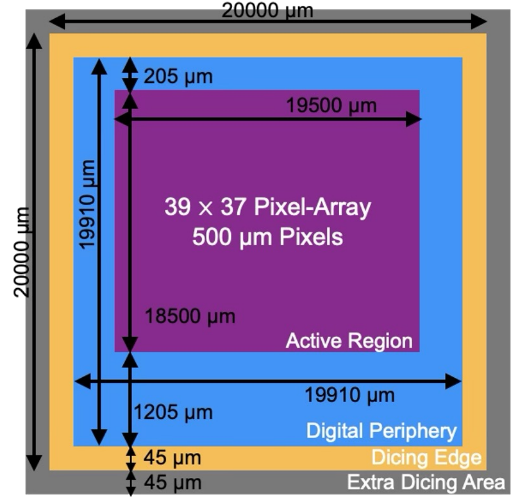
Pixel matrix 5.3 mW

Digital 2.2 mW

— 700 uW DigitalTop

Total: ~2 mW/cm^2 for 2x2 cm^2 chip

AstroPix v6 will be scaled up to **20 mm ✕ 20 mm** chip size

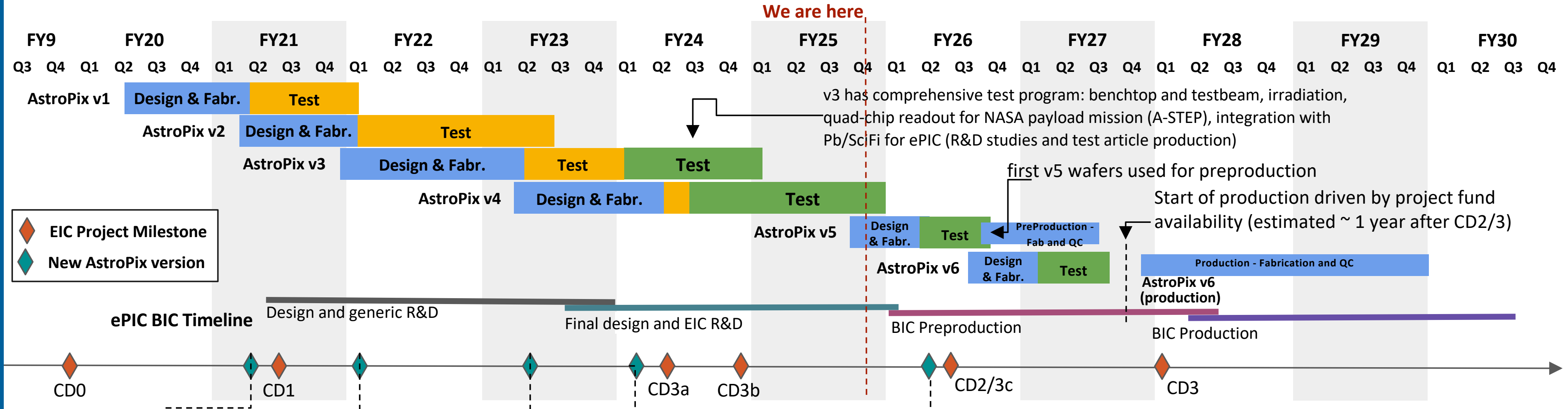


AstroPix v6 do not expect major design changes. Scaled up chip size to required 2 cm ✕ 2 cm dimension with bug fixes and selection of dynamics range feedback and NMOS comparator.

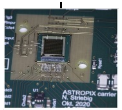
AstroPix Timeline

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

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



*Dec 2031 - ready for installation at BNL



AstroPix v1

HV-CMOS MAPS based on ATLASPix3, designed for the AMEGO-X NASA mission, optimized for power dissipation and energy resolution

Nucl.Instrum.Meth.A 1019 (2021) 165795

0.45 x 0.45 cm^2 chip, 175 µm pixel pitch
18 x 18 pixel matrix
Power dissipation 14.7 mW/cm^2

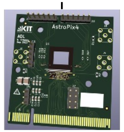
AstroPix v2

1 x 1 cm^2 chip, 250 µm pixel pitch
35 x 35 pixel matrix
Row/column readout
Power dissipation 3.4 mW/cm^2

AstroPix v3

First full-size chip

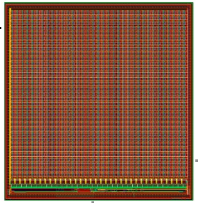
2 x 2 cm^2 chip, 500 µm pixel pitch
Row/column readout
Power dissipation <1 mW/cm^2
2.5 MHz timestamp, 200 MHz ToT



AstroPix v4

Final design but smaller size

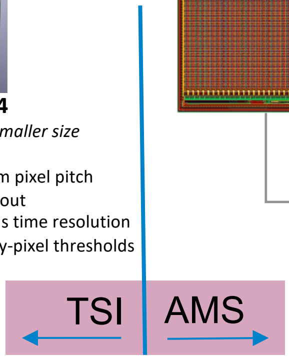
1 x 1 cm^2 chip, 500 µm pixel pitch
Individual pixel readout
3 timestamps, 3.25ns time resolution
TuneDAC for pixel-by-pixel thresholds



AstroPix v5

pre-production chip

1.87 x 1.9575 cm^2 chip, 500 µm pixel pitch
Design identical to v4 (with bug fixes and modification for **AMS foundry**)



AstroPix v6

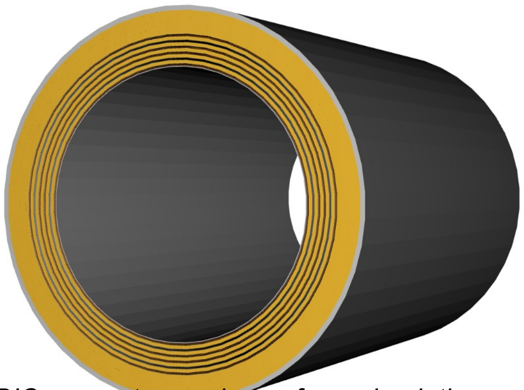
production chip

2 x 2 cm^2 chip, 500 µm pixel pitch
Design identical to v5 (with bug fixes)

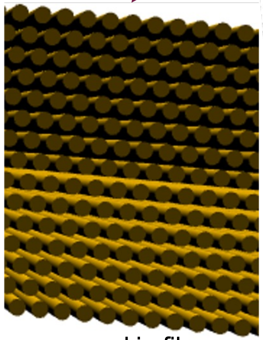
36

Simulations

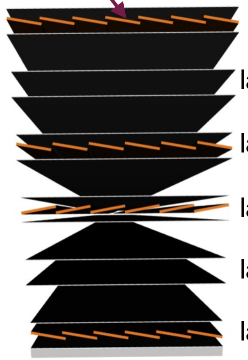
- **Simulation** results based on realistic detailed simulations benchmarked in beam and bench environment.
- **Official ePIC geometry implementation** with realistic detailed BIC geometry implemented
    - Full detector with all subsystems, the majority of services
    - Cladded SciFi placed in Pb and glue mixture
    - AstroPix layers: “turbofanned” staves with chips; expected dead areas included
- **Realistic digitization and reconstruction** with effective model for the optical output including:
    - **light attenuation and phe statistics** (benchmarked in GlueX and adjusted for fiber differences)
    - **light guide efficiencies** from optical simulations
    - thresholds based on **SiPM HGCROC-template noise**
- EM and Had responses in **simulations benchmarked with the beam test data up to 10 GeV**



*BIC geometry rendering from simulations with **SciFi/Pb** and **AstroPix layers***



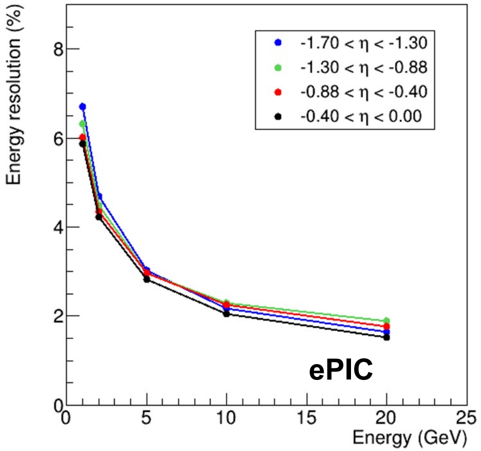
zoomed in fibers



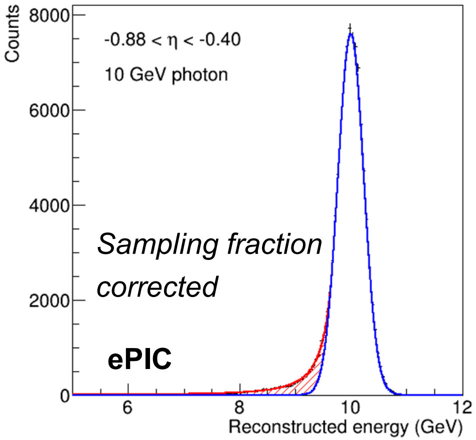
Energy Response
Photons

- Energy resolution meets requirement < 10%/√(E) + (2-3)%
- Benchmarked in beam tests.

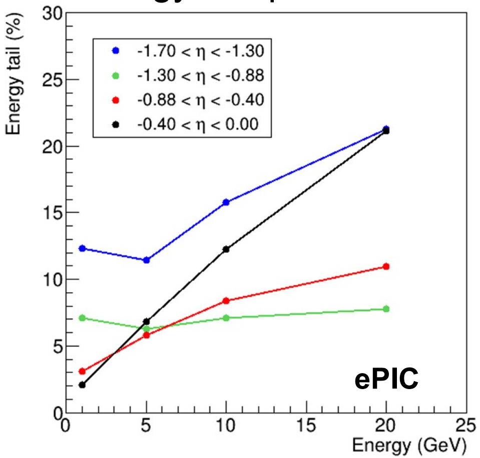
Energy Resolution



Energy Deposit Shape



Energy Response Tail



Fit parameters

η	a/√(E) [%]	b [%]
(-1.7, -1.3)	6.60(0.03)	0.66(0.04)
(-1.3, -0.88)	6.11(0.01)	1.24(0.01)
(-0.88, -0.4)	5.91(0.02)	1.24(0.02)
(-0.4, 0)	5.85(0.01)	0.88(0.02)

- Based on the realistic simulation of the Pb/ScFi part of the calorimeter with attenuation and photoelectron statistics
- Resolution extracted from a Crystal Ball fit σ
  - Energy tail evaluated as a difference between the Crystal Ball and the extrapolated Gaussian fit

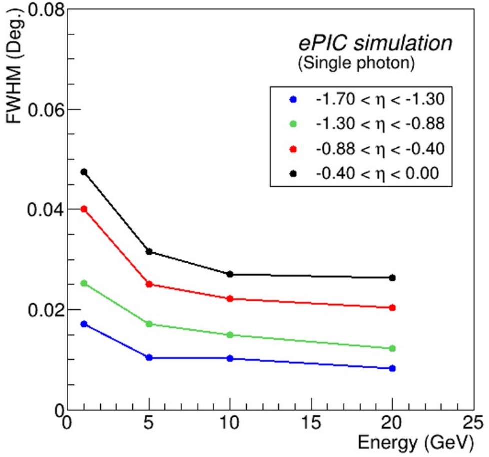
Position Response with AstroPix

Photons

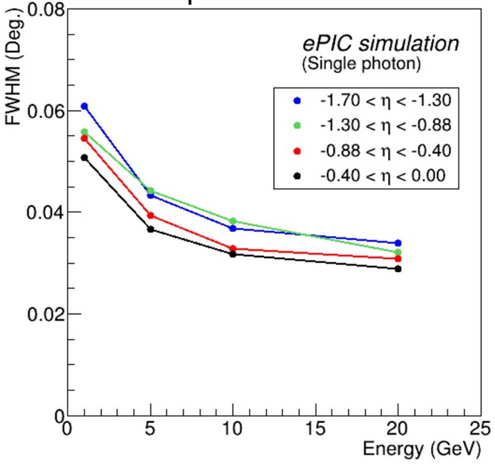
- Angular resolution well below 0.1 deg (on the level of single pixel resolution) well below any tower-like calorimetry
- Position measurements benchmarked in beam tests

- **Methods:** max-deposit hit at the shower-start layer compared to θ, ϕ from 3D topological clustering. **Result:** hit-level method gives an order of magnitude better angular resolution.
- Small dependence seen with changing η. The ϕ resolution is worse than θ because the shower particles are smeared by the magnetic field.

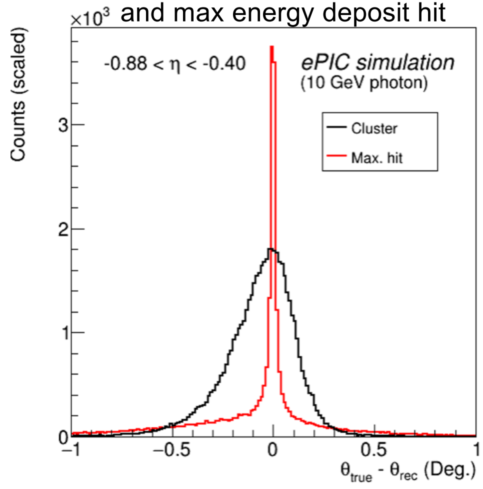
θ resolution



φ resolution



θ true - θ reconstructed from cluster and max energy deposit hit



39

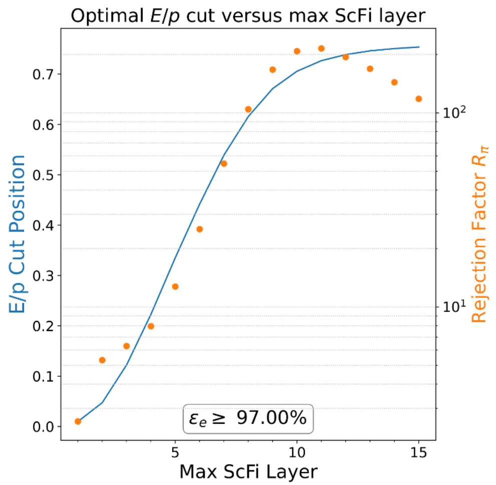
Particle Identification

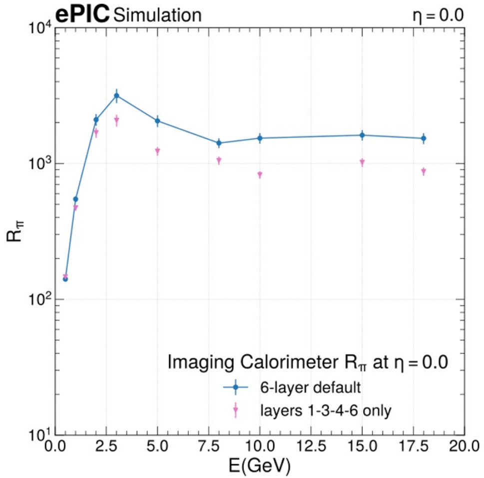
Electrons and Pions

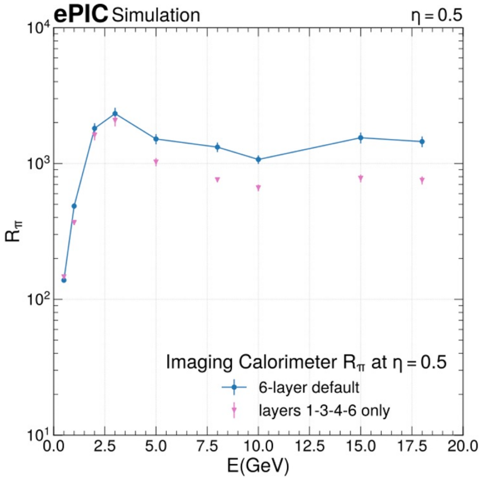
- High e/π separation down to 1 GeV/c delivers required ~90% electron purity with combined ECAL+DIRC. *See backup for more details.* (P-DET-ECAL-BAR.26.10.05)

Method: Optimized cut on E/p from different depth of Pb/ScFi layers at very high electron efficiency + **Convolutional neural network** utilizing energy and spatial information for shower

Example for 2 GeV e/π







Scan through different number of SciFi/Pb layers to find the optimal maximal depth. **Peak ~ layer 10-11**

Pion rejection: 4-layer achieves >10³ at low–mid energies where it is most needed; 6-layer achieves >10³ across most energies and is a good upgrade option for high-luminosity, higher-energy runs.

Sectors and Mechanics

Design constraints defined and mostly frozen; geometries and envelopes documented; BIC and Project engineers aligned.

Design challenges: self-supporting sector with ePIC integration; FEA in progress using delamination data at CF–Pb and Pb/SciFi interfaces.

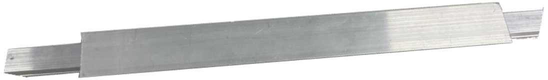
Sector test articles:

- 0.5 m GlueX-style matrix reproduction completed, critical equipment commissioned. SciFi QC procedure established.
- Short bulk Pb/SciFi with GlueX fibers and CF-frame integration ongoing
- Long 3 m article next; full-scale 4.35 m sector for preproduction targeted for 2026

AstroPix tracker mechanics: staves integrated into trays → modules slide onto trays → trays slide into sector drawer/slot.

- First extruded-aluminum mechanical article built and tested for tolerances and stability


Pb/SciFi matrix build and tested at ANL

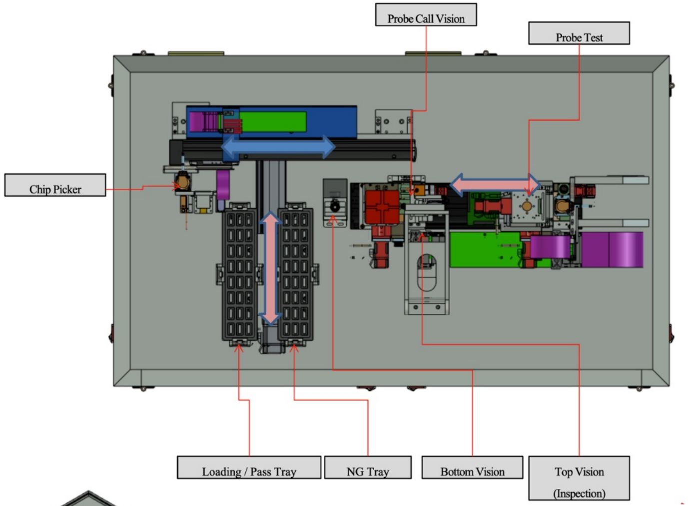

First tracker test article - module base with stave like railing


Upgraded swager inherited from U. Regina fully operational


Press frame @ Argonne in our new sector production space (5500 sq ft)

Mechanical risks are under active test with a defined path to full-scale sector in 2026. First test articles of tracker support and SciFi matrix tested.

Wafers and Modules

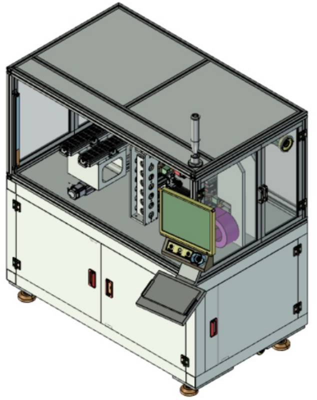


Chip testing scope

- **Scale:** 31,104 modules, 279,936 AstroPix chips.
- **Need:** automated chip-level testing before module assembly with established QC procedures.
  QC coverage: sensor bias with HV, analog and digital checks, injection scans for relative energy calibration.

v3 Pilot (this fall → 2025 Q4)

- **Probe card:** simple v3 card for the carrier board, built with a Korean manufacturer; uses validated GECCO + FPGA setup; leverages ALICE experience
- **Throughput target:** validate the QC flow on ~80 v3 chips this fall
- **Automation:** single-chip v3 test machine from C-ON Tech due 2025 Q4 to run initial validation, refine the test flow, document the full chain, and deliver qualified v3 chips for prototype modules



Single-chip v3 test machine is under production by C-ON tech in Korea

Preproduction (v5/v6, FY26-FY27)

- **Design update:** v5 ready in FY26 for preproduction
- **Process readiness:** finalize procedures and acceptance criteria

We are moving from a validated v3 pilot to a preproduction workflow for v5/v6, establishing throughput, traceability, and acceptance criteria needed to de-risk delivery of 280k+ chips for 31k modules.

Wafers and **Modules**

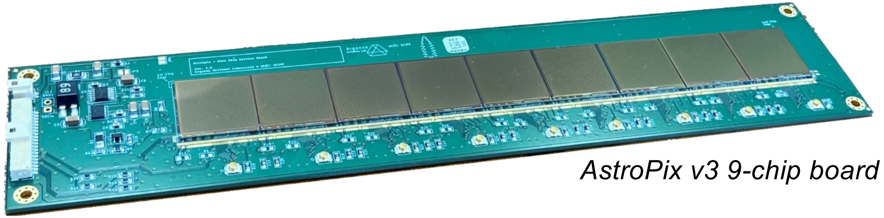
Scope: single-flavor module for more than 30,000 units

AstroLinx (PCB): optimized for module performance, meets required operation specs; first design completed and reviewed. Expected this fall; another iteration anticipated.

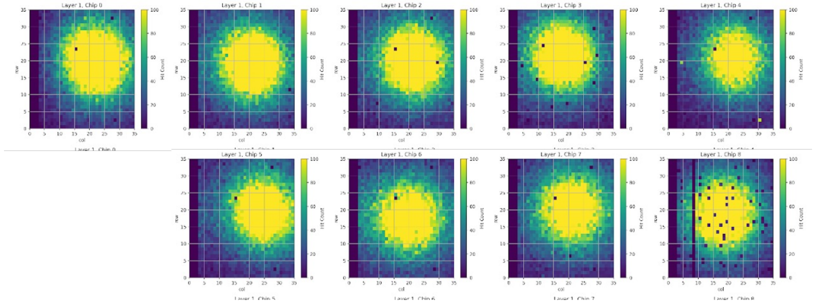
9-chip PCB test article: In hand to mock up AstroLinx, verify power-distribution stability and daisy-chain readout. Successfully tested on a bench with sources.

Module builds: plan to assemble about six prototypes this fall using an extruded aluminum base, AstroPix v3, and AstroLinx; test PCB designed to validate electrical performance; initial base-plate prototype produced to define assembly steps.

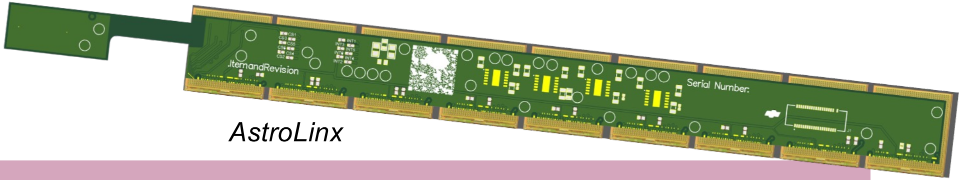
Open design items: base-plate locking mechanism, adhesive selection, flex-PCB connector finalization



AstroPix v3 9-chip board



Daisy chain readout through 9 chips with source scan



AstroLinx

AstroLinx has been reviewed and the 9-chip PCB validated with sources; we are proceeding to module test articles to lock performance and assembly while closing the few remaining design choices for preproduction.

ESB (End of Sector Box) and DAQ

Function: on-detector power distribution and data collection. Encloses cooling and provides mechanical protection.

Interfaces with ePIC: integration procedure nearly final; service requirements provided (electrical cabling, cooling, DAQ).

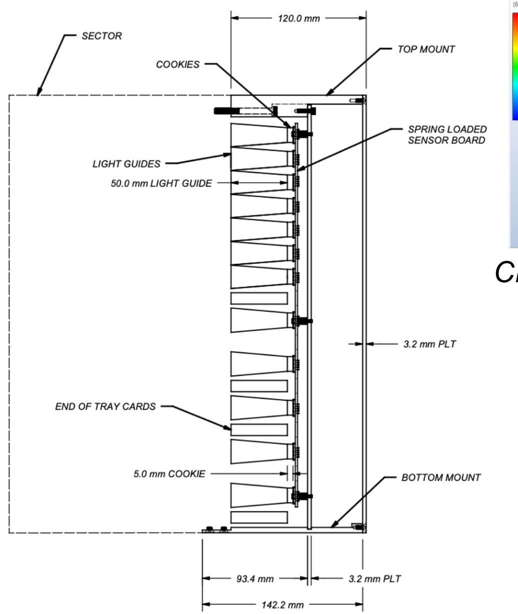
Thermal/mechanical validation: Ongoing: development and construction of PCB (thermal) test article to validate CFD calculations.

SiPM readout path: CALOROC → common RDO → FELIX.

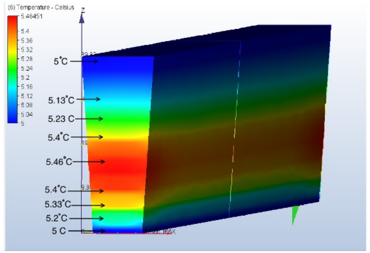
- Lightguides design complete, geometry fixed.
- CALOROC design under submission; evolution of HGCROC with CMS and ALICE heritage.
- SiPMs passed FDR at CD-3a/3b.

AstroPix readout path: End-of-Tray Card (ETC) → FELIX.

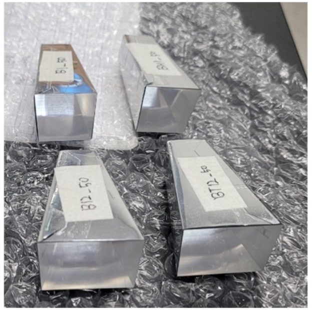
- ETC to be designed by NASA GSFC; start pending contract processing; leverages existing AstroPix FPGA board designs.



ESB Envelope



CFD Calculations Performed


LG test articles validated

ESB envelope and interfaces nearly finalized; CALOROC at submission; ETC awaits contract start, with existing designs reducing risk. SiPM design completed. Lightguides and cookies nearly finalized.

System Testing

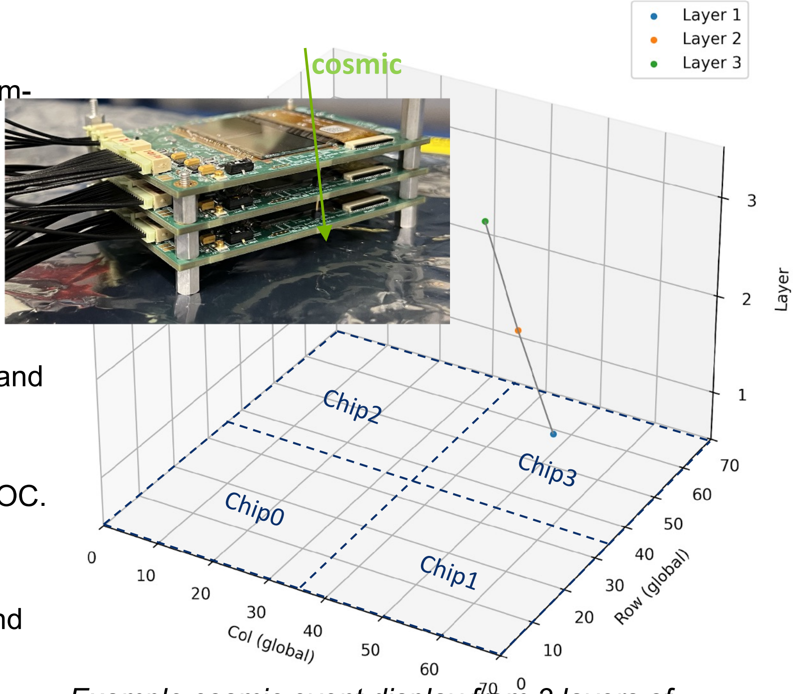
Function: validate system-level performance and design, establish system-level QC/QA procedures.

AstroPix imaging layers: multichip and multilayer test articles to demonstrate daisy-chaining, synchronization, and energy, position, and timing response; bench and beam tests completed.

Pb/SciFi calorimetry: Bulk (~15.5 X_0) and SFILs (~1.5 X_0) tested with e and π beams, validating energy response and e/π separation in the Pb/SciFi section; simulations benchmarked.

- **ANL-built SFILs:** first units show good MIP response with HGCROC.

Large-scale integration (PED, PREP): readout and large-test-article integration underway to validate system-level performance, calibration, and QC/QA at the AstroPix Tray and Sector levels; outputs will also inform component-level QC procedures.



Example cosmic event display from 3 layers of daisy-chained AstroPix v3 quad chips

The testing program de-risks the design and defines system QC/QA for production; current validations confirm calorimeter energy performance and rate capability, and validate the simulation against data.

Production Plan

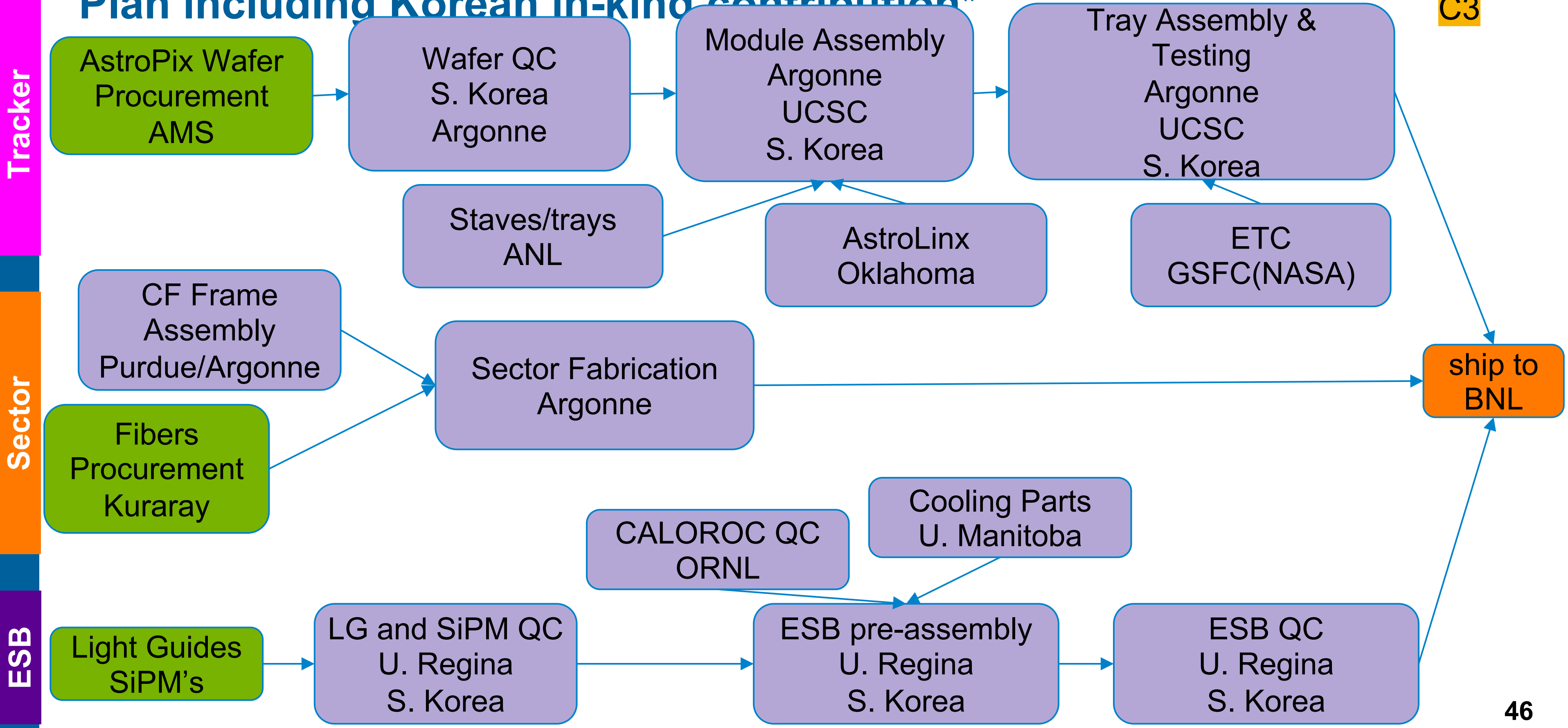
*iCRADA still to be signed

vendor

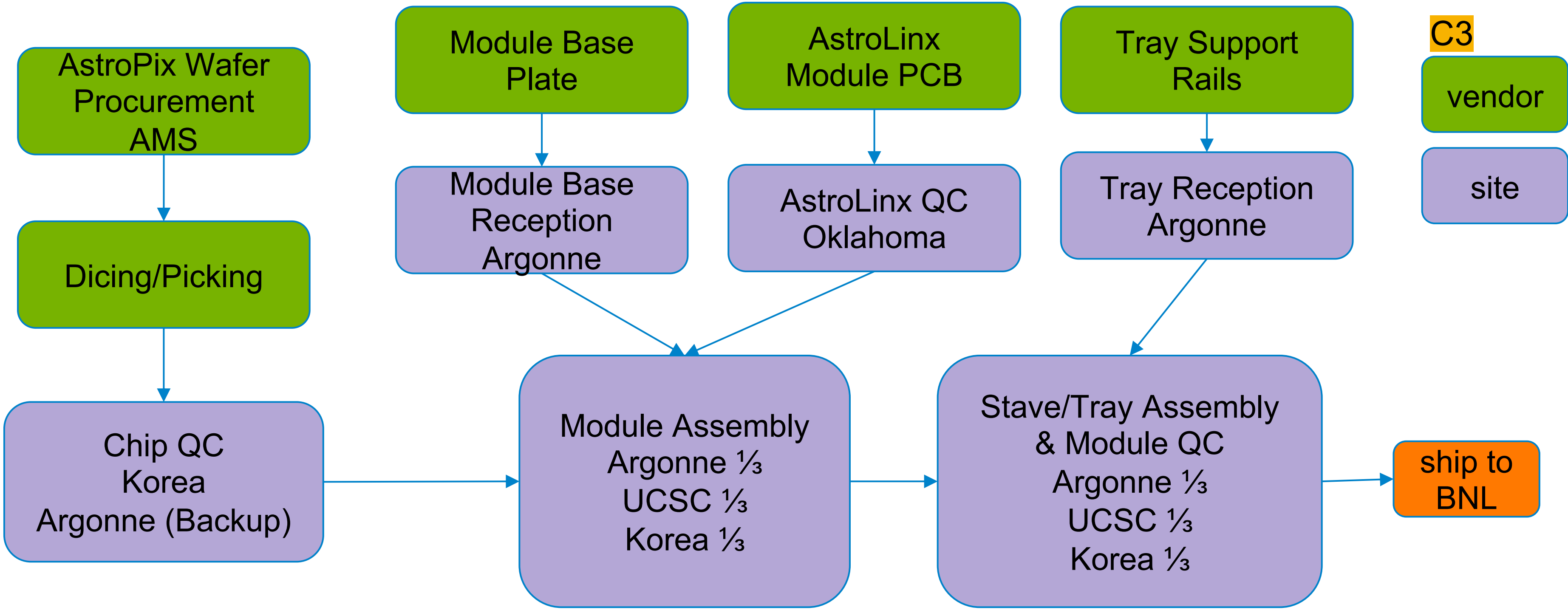
site

Plan including Korean in-kind contribution*

C3



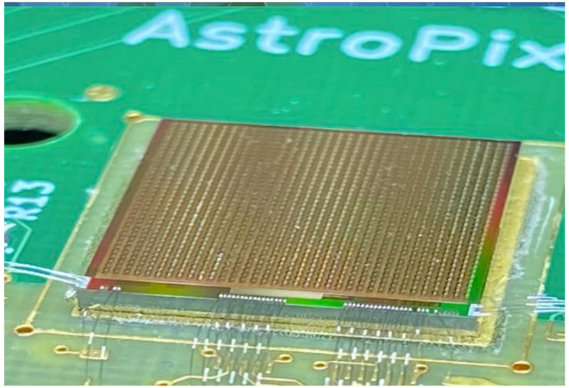
Workflow: Tracker Layers



- Wafer procurement with AMS
- One flavor for each part
- Thorough QC at bare chip level to ensure good chips/sensors
- Keep all steps as simple and streamlined as possible for industrial style manufacturing

Wafer QC Probing

1. Purchase wafers
2. Dicing
   a. picked by vendor, comes in a waffle pack
3. Automated wafer (or chip) QC probing
   a. Visual inspection
   b. Full chip functionality
   c. Sensor IV
   d. Pixel-by-pixel performance
4. Ship to module assembly sites

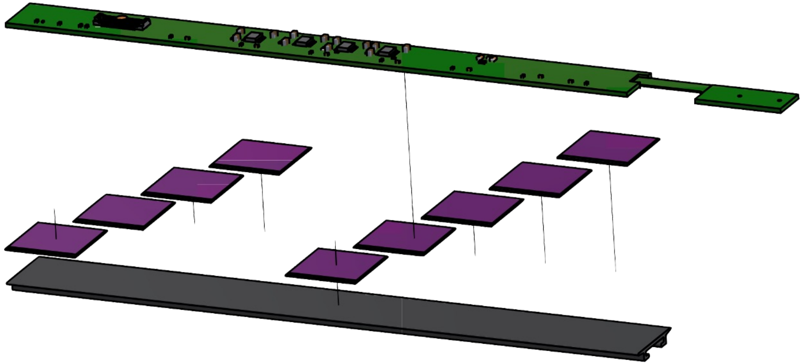


→Expect to have a high yield after chip testing until glued on a module

Wafer QC	# parts	# per batch	# batches	hours/batch	minutes/piece	# people	Total Person hours	Inactive hours/batch	Batches/week/production line	# of production lines	Total production weeks	Total production years (w/ 85% annual efficiency)
chip probing	357,319	60	5,956	5	5	1	596	4.9	15	6	66	1.5

Module Assembly

1. Stage chips and module base plates onto the tooling
2. Glue chips to the base plate, cure
3. Stage the module and AstroLinx onto the tooling
4. Glue AstroLinx to the module, cure
5. Wire bond
6. Pot wire bonds (under consideration)



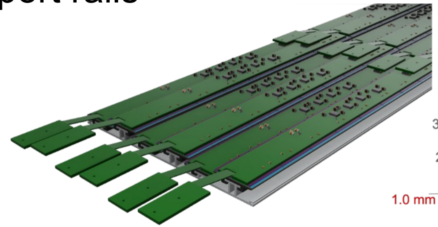
Module Assembly	# parts	# per batch	# batches	hours/batch	minutes/piece	# people	Total Person hours	Inactive hours/batch	Batches/week/production line	# of production lines	Total production weeks	Total production years (w/ 85% annual efficiency)
chip reception	303721	100	3037	0.17	0.1	1	506	0	240	3	4	0.10
module gluing	33747	6	5625	5	-	1	2812	4.5	5	18	63	1.4
gluing AstroLinx	33747	6	5625	5	-	1	2812	4.5	5	18	63	1.4
wire bonding	33747	1	33747	0.25	15	1	8437	0	160	3	70	1.60
potting	33747	6	5625	0.17	1.7	1	937	8	240	3	8	0.18

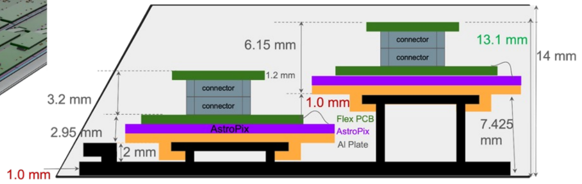
Stave/Tray Assembly

1. Slide modules onto *the bottom row* of the tray support rails
2. plug connectors, quick test, rework
3. Slide modules onto *the top row* of the tray support rails
4. plug connectors, quick test, rework
5. Full electrical QC w/ end-of-tray card
6. Pack and ship to BNL

<u>Reworkable design:</u>

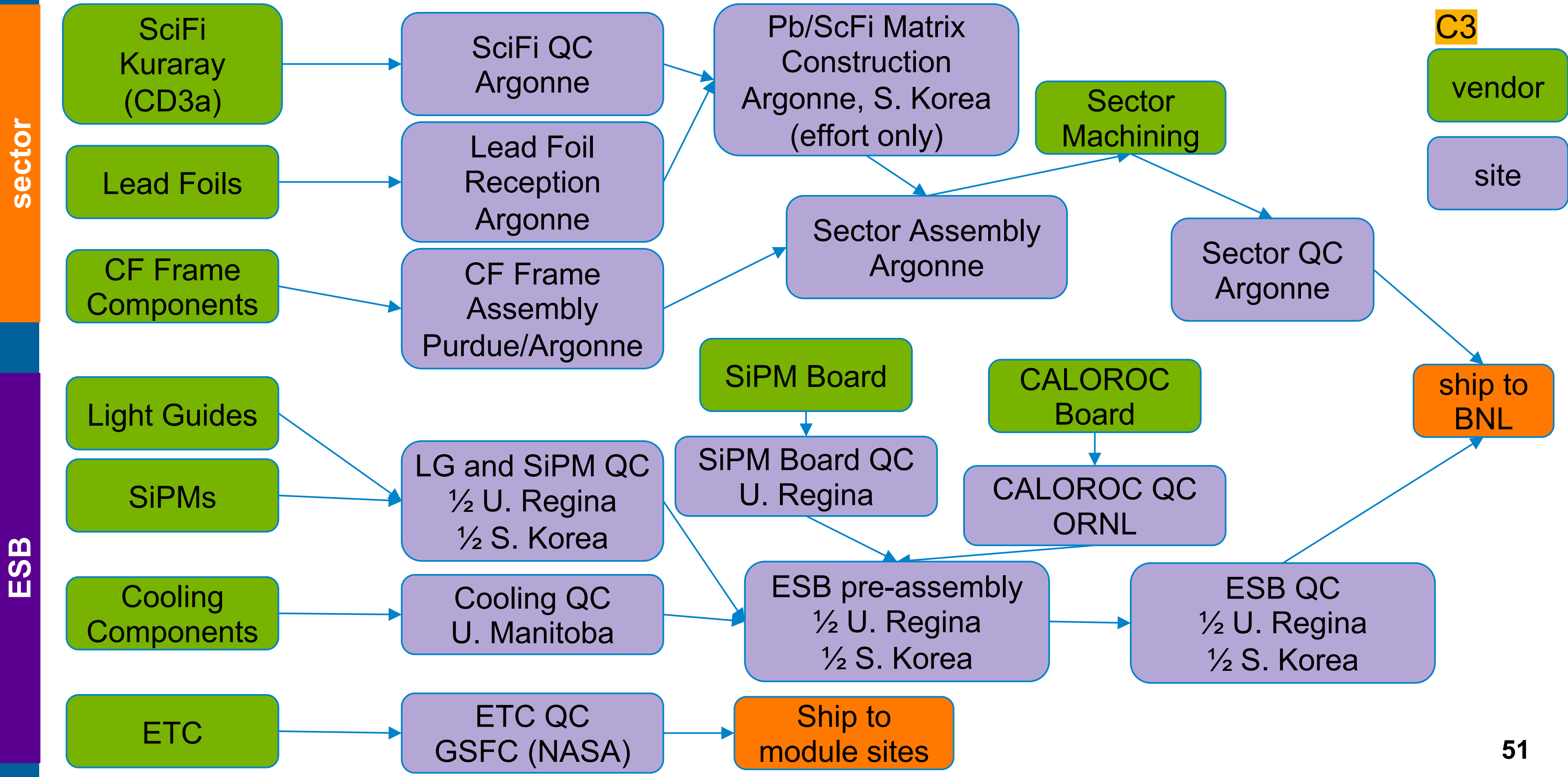
- connectors rated for mating cycles
- no gluing



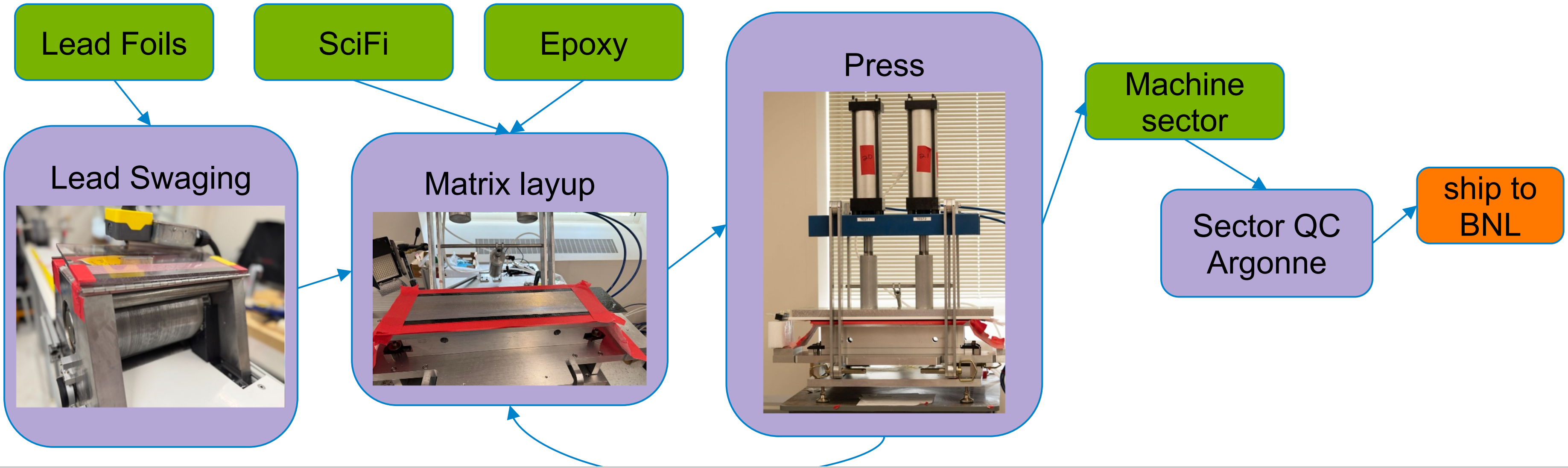


Tray Assembly	# parts	# per batch	# batches	hours/batch	minutes/piece	# people	Total Person hours	Inactive hours/batch	Batches/week/production line	# of production lines	Total production weeks	Total production years (w/ 85% annual efficiency)
assemble modules on tray	388	1	388	5	300	1	1940	0	8	3	16	0.37
Tray electrical QC	388	1	388	0.5	30	1	194	48	3	3	43	0.98
packing	388	1	388	0.5	30	2	388	0	80	3	2	0.04

Workflow: Pb/SciFi Sectors & ESB



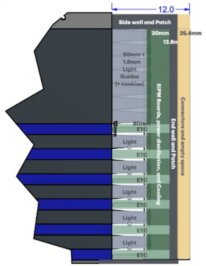
Production Plan: Mechanical Sector



Sector Assembly	# parts	# per batch	# batches	hours/batch	minutes/piece	# people	Total Person hours	Inactive hours/batch	Batches/week/production line	# of production lines	Total production weeks	Total production years (w/ 85% efficiency)
Fiber QC (1%)	10000	208	48	52	15.0	2	104	104	0.8	1	62	1.4
Matrix layup	576	12	48	75	377	5	377	377	0.3	2	90	2.0
CF Frame Integration	288	6	48	16	160	2	32	80	1.3	2	19	0.4
Sector QC	48	1	48	8	480	2	16	16	5.0	1	10	0.2

Production Plan: End-of-Sector Boxes

- component parts QC
- pre-assembly of ESB
  - SiPM’s, CALOROC, cooling
- ESB QC
- Final assembly at BNL



Sector Assembly	# parts	# per batch	# batches	Active hours/batch	minutes/piece	# people	Total Person hours	Inactive hours/batch	Batches/week/production line	# of production lines	Total production weeks	Total production years (w/ 85% annual efficiency)
Light guide	5933	60	99	2	2	1	198	12	5	1	20	0.45
SiPM board QC	6022	60	101	2	2	1	202	12	5	1	22	0.5
CALOROC PCB QC	101	1	101	2	120	1	202	0	20	1	5	0.11
End-of-tray card QC	106	1	106	2	120	1	212	0	20	1	5.3	0.12
Cooling QC	100	1	100	0.5	30	1	50	0.5	40	1	2.5	0.06
ESB pre-assembly/QC	100	1	100	2	120	2	400	0	20	1	5	0.11