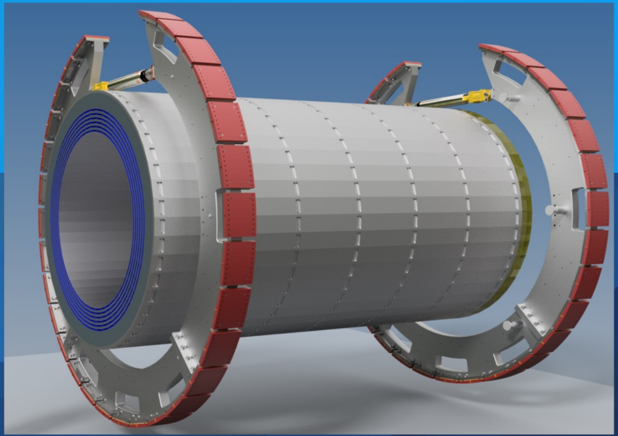
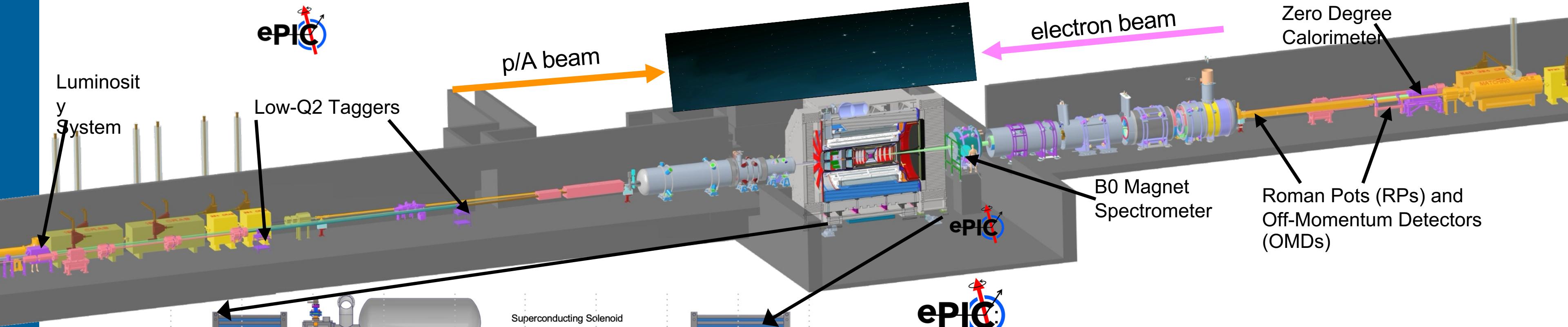
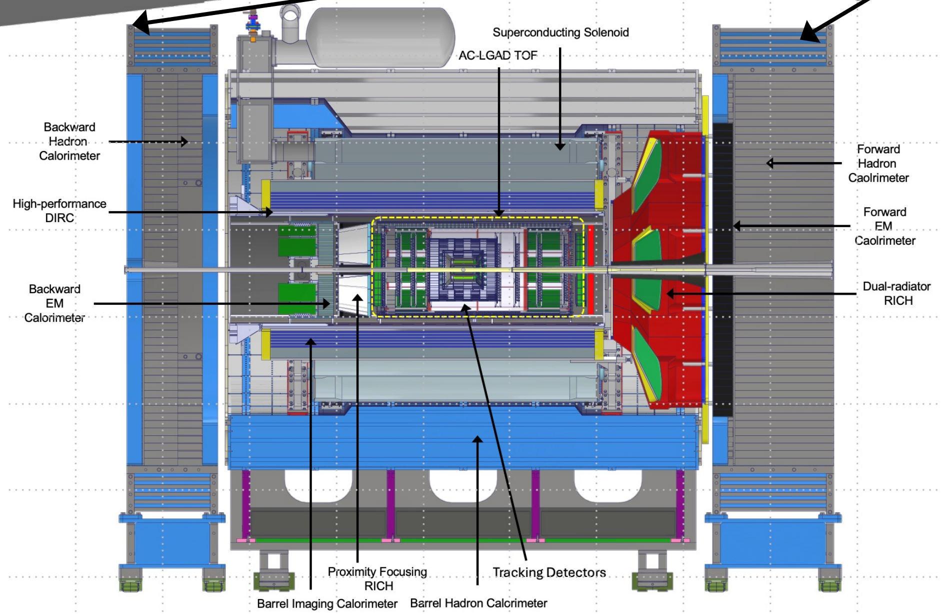
# Development and Performance of AstroPix for the ePIC BIC Detector



**Sanghoon Lim**
Pusan National University

# ePIC – The EIC General-Purpose Detector




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/

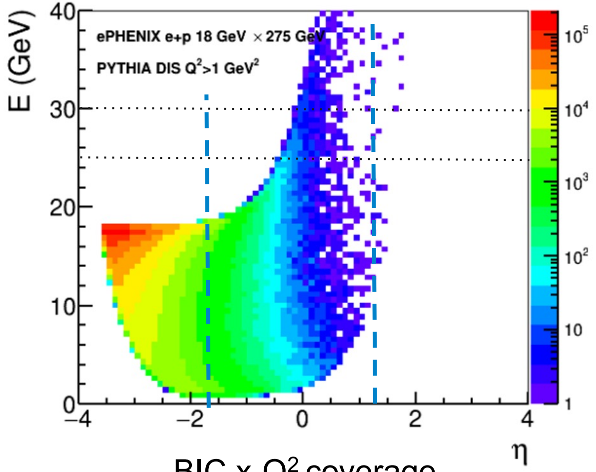
Identify scattered electrons and measure their energy, in high $Q^2$ events, also decay electrons, e.g., from vector or heavy flavor meson decays, and measure DVCS photons and decay photons

- **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**
- **ɣ/π⁰ separation up to 10 GeV**
  - Distinguishing two showers with an opening angle down to 30 mrad

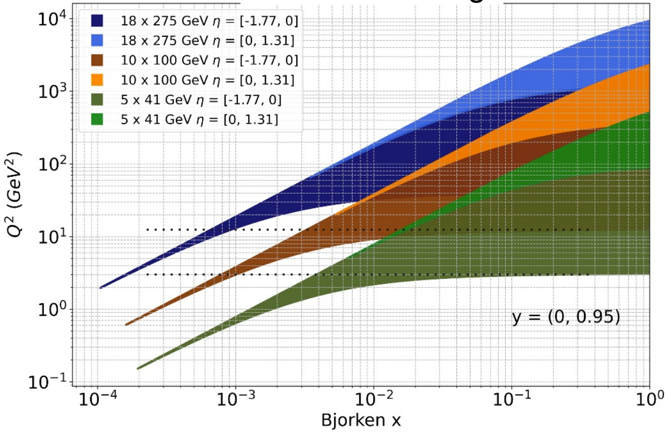
**Assist with muon identification**

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

DIS electrons

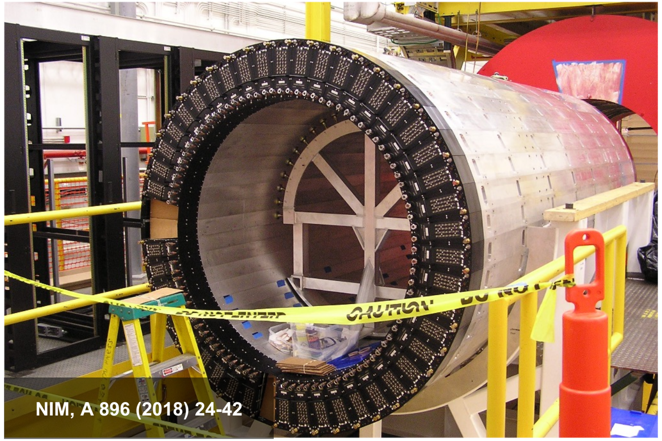



BIC x-Q² coverage



# A Hybrid Imaging Calorimeter

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




NIM, A 896 (2018) 24-42

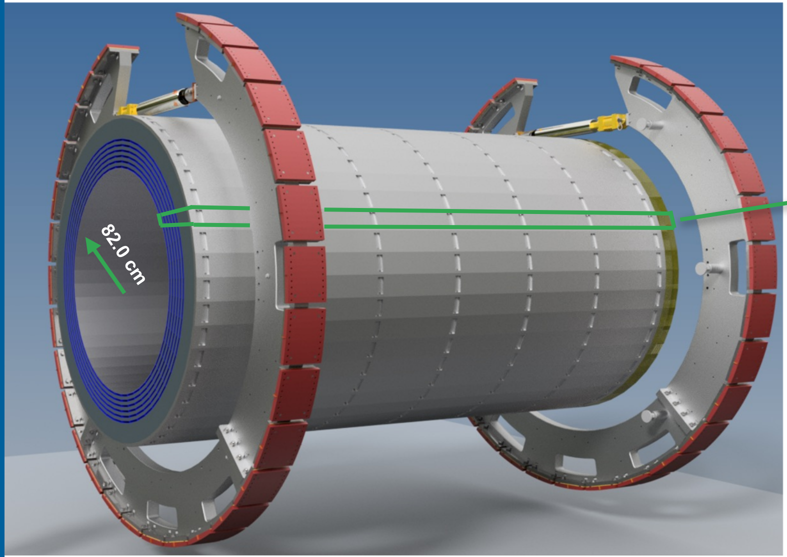

NIM, A 1019 (2021) 165795

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

# Barrel Imaging Calorimeter

## Sector Mechanics

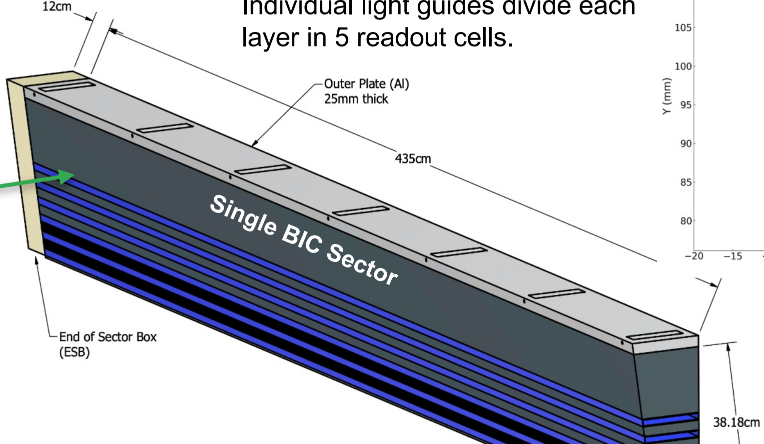


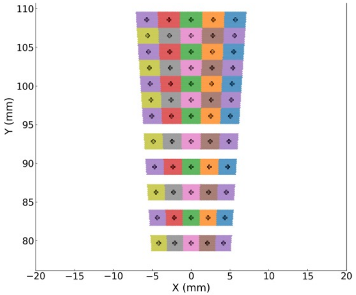

Total BIC weight ~42.5 US tons

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

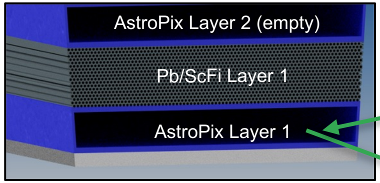
Each sector has 12 Pb/ScFi layers.

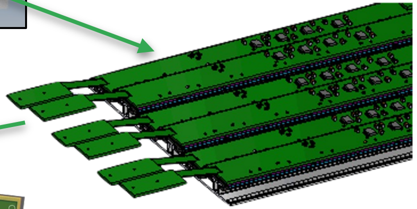
Individual light guides divide each layer in 5 readout cells.




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



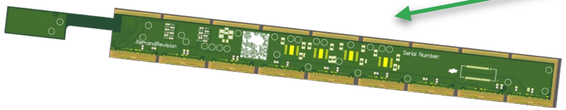



**Tray** - Structure holding the AstroPix staves for a single layer (217.5 cm long).

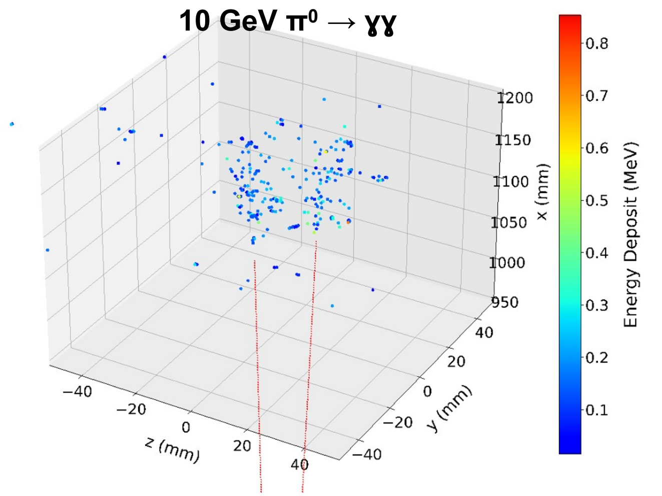
**AstroPix Module** - Nine AstroPix sensors daisy-chained together on Flex PCB.

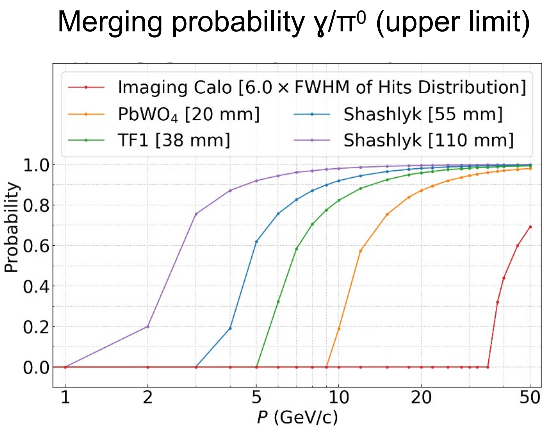
A stave consists of 12 modules.

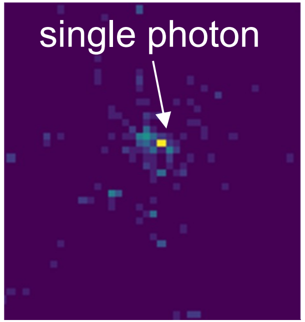
A tray contains of 6-8 staves.

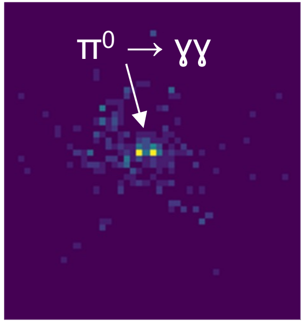


# Particle Identification
## Photons and Neutral Pions



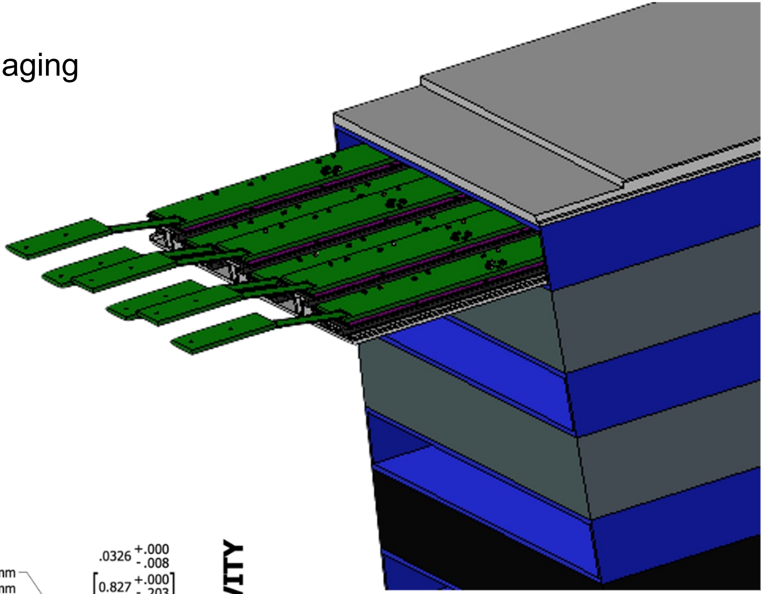



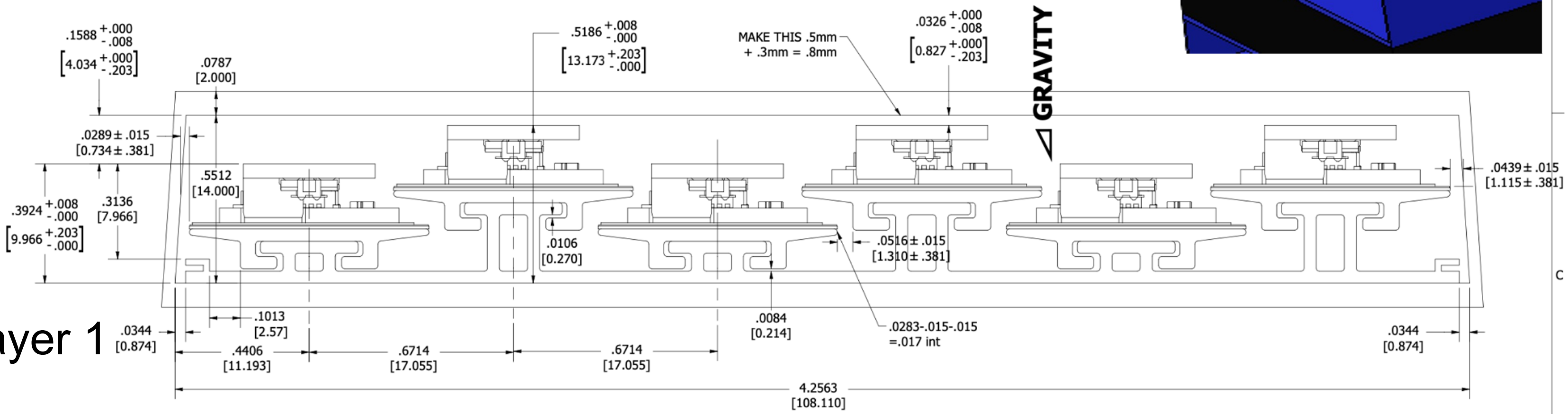




- Precise position resolution and shower imaging allow for excellent separation of $\gamma/\pi^0$ **based on the 3D shower profile**
- Upper limit unticipated from the **AstroPix position resolution and shower profile: well above 10 GeV**
- First insights from a simple **neural network approach**
(**~82%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

# 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

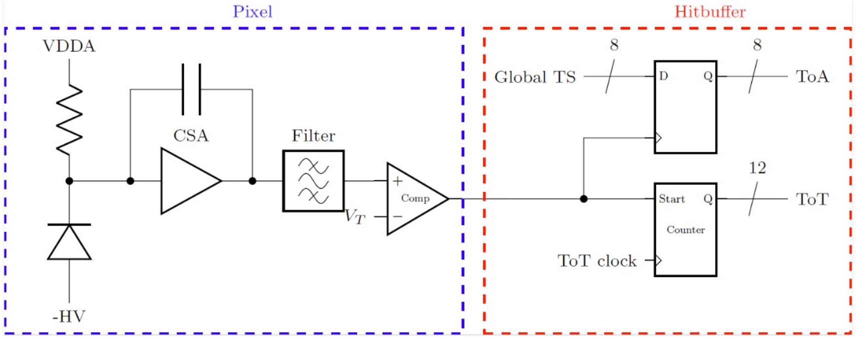
# Imaging Layer Technology

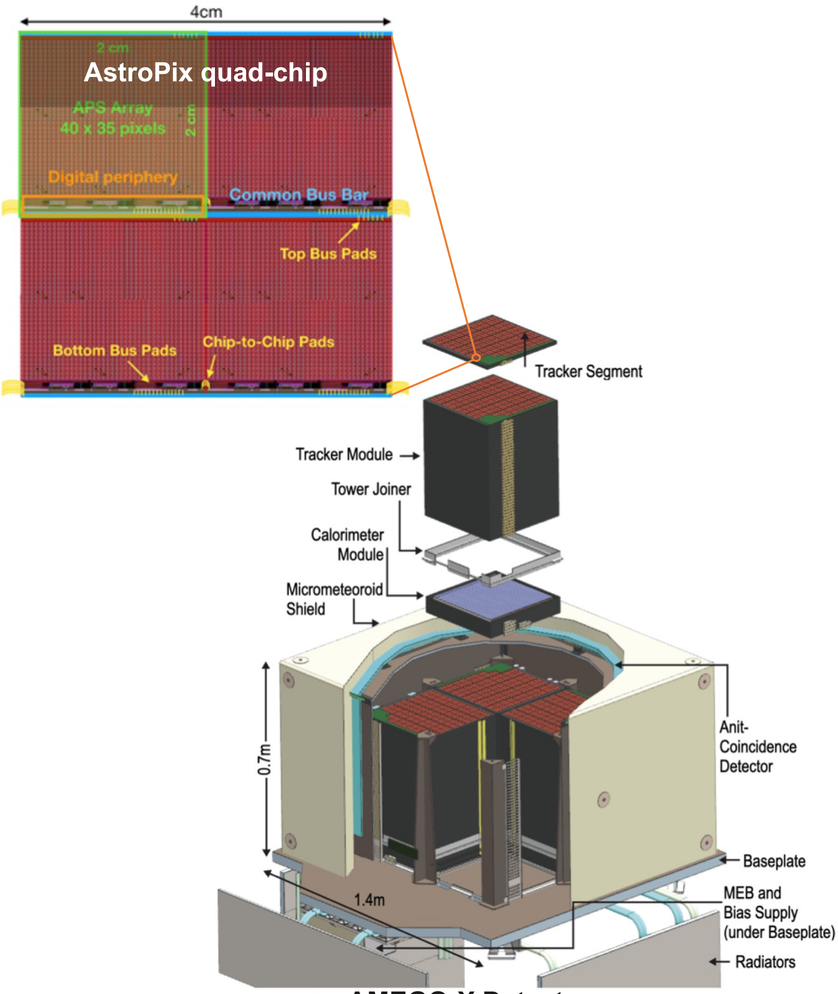
**Imaging layers will use the AstroPix sensors**

- 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)
- 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]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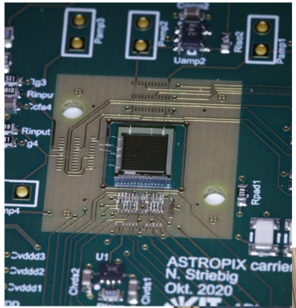
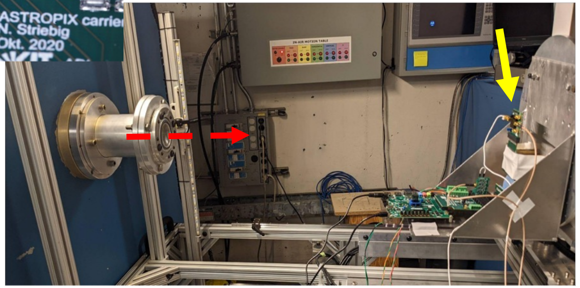
# Overview of AstroPix

## 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

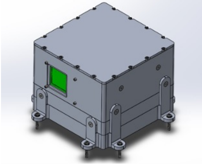
Second prototype

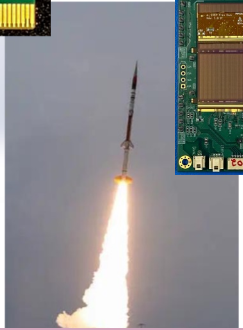

Radiation testing April, June 2022

### 2023 AstroPix v3

Flight prototype


AStep: 3-layer quad-chip payload launch: FY26





**Beam Test FNAL 2023, 2024***

AstroPix selected for BIC

### 2024 AstroPix v4

Pixel readout, power reduced

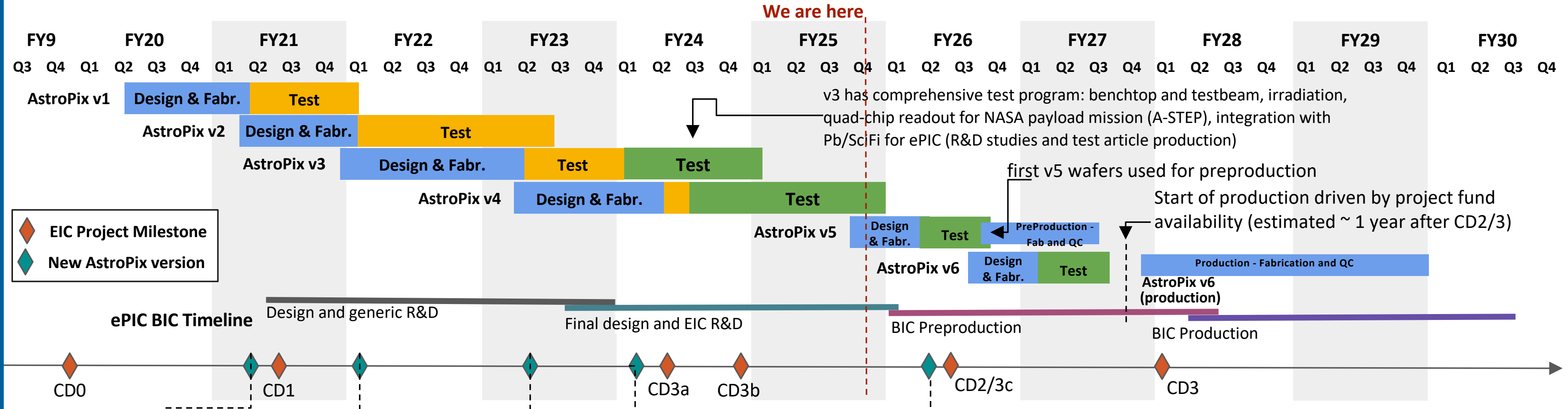

Chips tested at GSFC, ANL, Hiroshima, etc

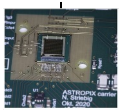
All produced by TSI Semiconductors

# AstroPix Timeline

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

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



**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 cm² chip, 175 µm pixel pitch
18 x 18 pixel matrix
Power dissipation 14.7 mW/cm²

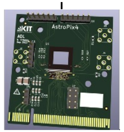
**AstroPix v2**

1 x 1 cm² chip, 250 µm pixel pitch
35 x 35 pixel matrix
Row/column readout
Power dissipation 3.4 mW/cm²

**AstroPix v3**

*First full-size chip*

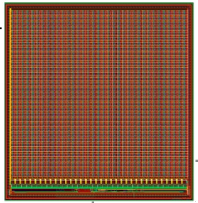
2 x 2 cm² chip, 500 µm pixel pitch
Row/column readout
Power dissipation <1 mW/cm²
2.5 MHz timestamp, 200 MHz ToT



**AstroPix v4**

*Final design but smaller size*

1 x 1 cm² 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 cm² chip, 500 µm pixel pitch
Design identical to v4 (with bug fixes and modification for **AMS foundry**)

**AstroPix v6**

*production chip*

**2 x 2 cm² chip**, 500 µm pixel pitch
Design identical to v5 (with bug fixes)

TSI | AMS

# AstroPix v5 Specifications

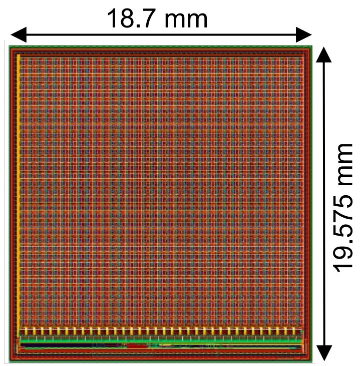
**Pixel Matrix:**

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
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)

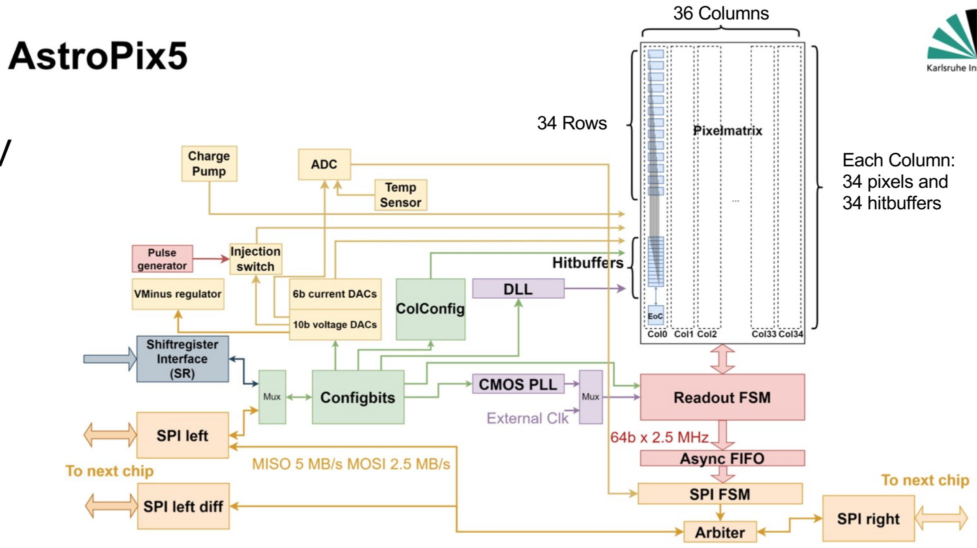
**Power Consumption:**

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

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:**

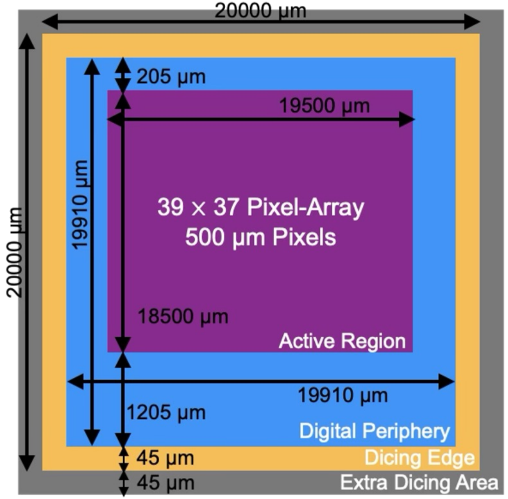
Pixel 4.6 uW

Pixel matrix 5.3 mW

Digital 2.2 mW

— 700 uW DigitalTop

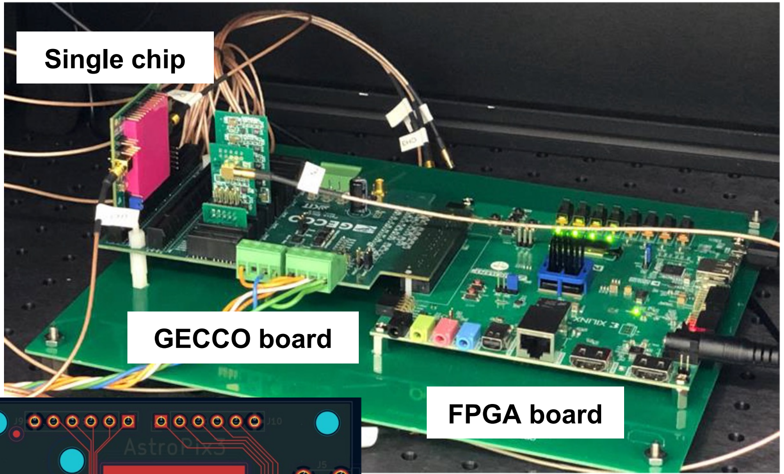
**Total:** ~2 mW/cm$^2$ for 2x2 cm$^2$ chip

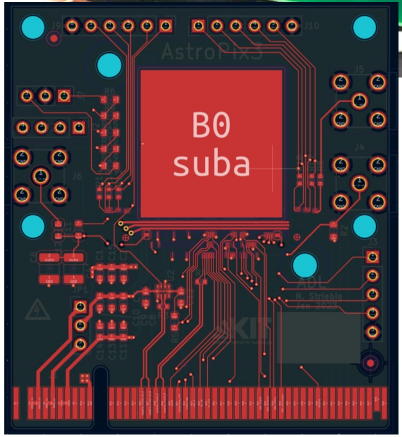



AstroPix v6 do not expect major design changes. Scaled up chip size to required 2 cm × 2 cm dimension with bug fixes and selection of dynamics range feedback and NMOS comparator.

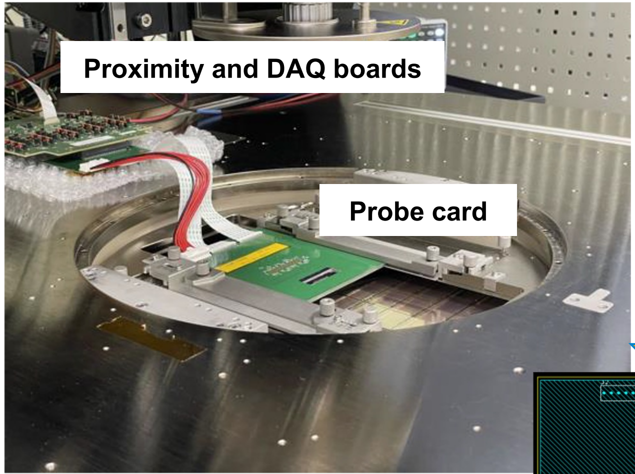
# AstroPix test system

### AstroPix v3 lab measurement setup

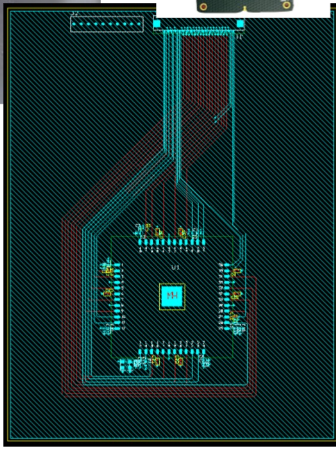



### ALICE ITS3 ER1 wafer probing system




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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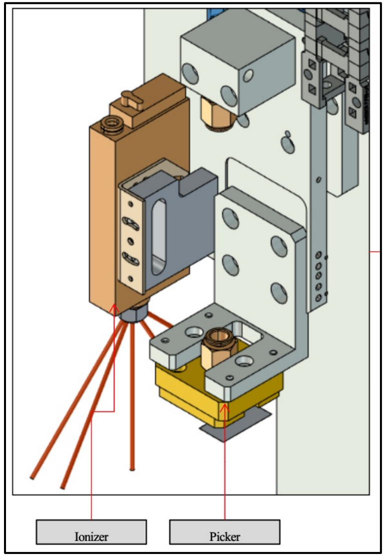
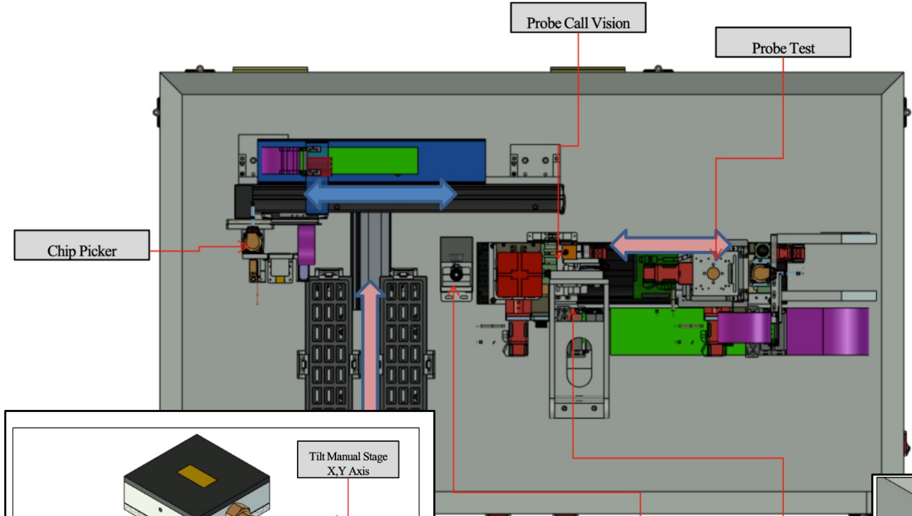
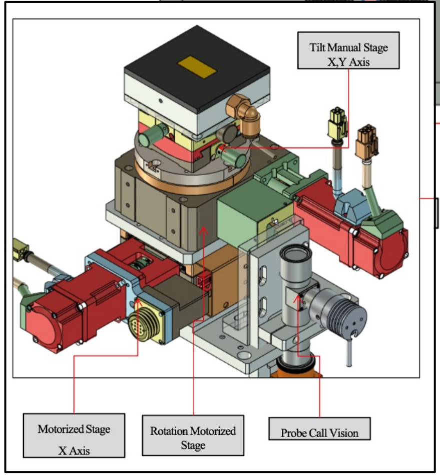
# AstroPix test system

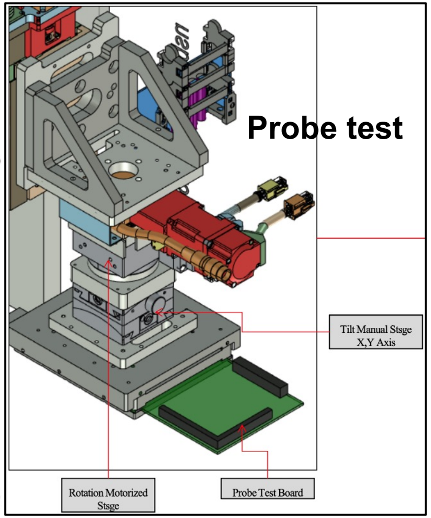


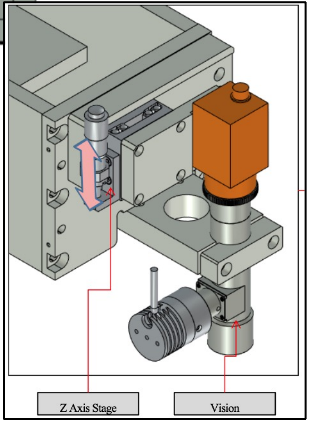

Sensor picker




Working stage




Vision inspection



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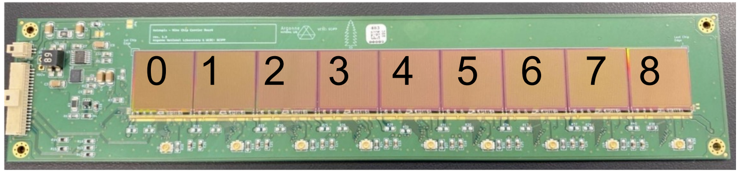
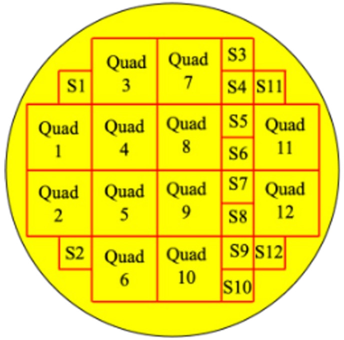
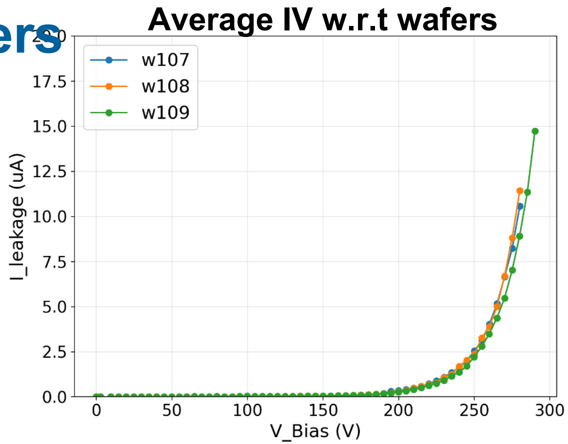
# Demonstration of Performance

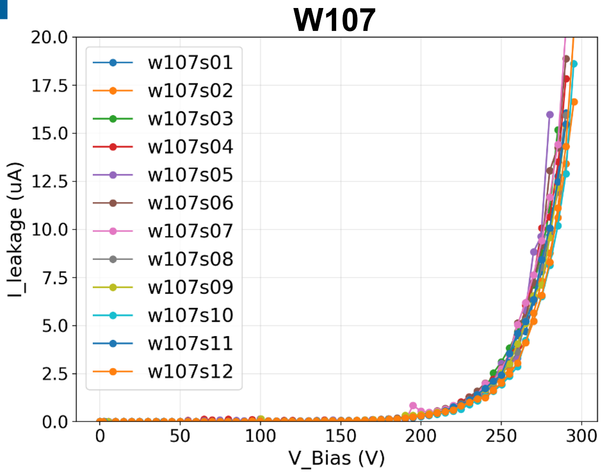
## IV trends as function of sensor location on wafers

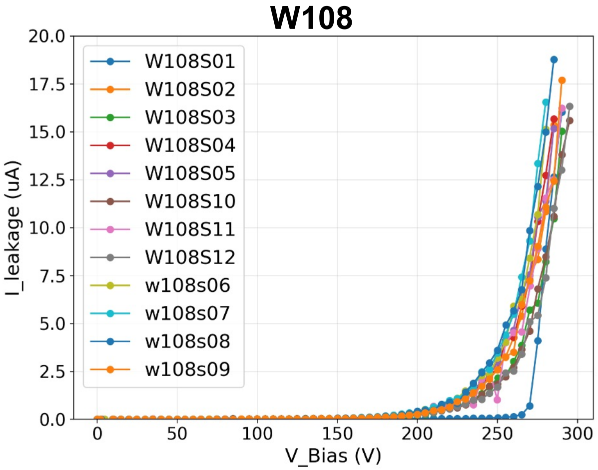


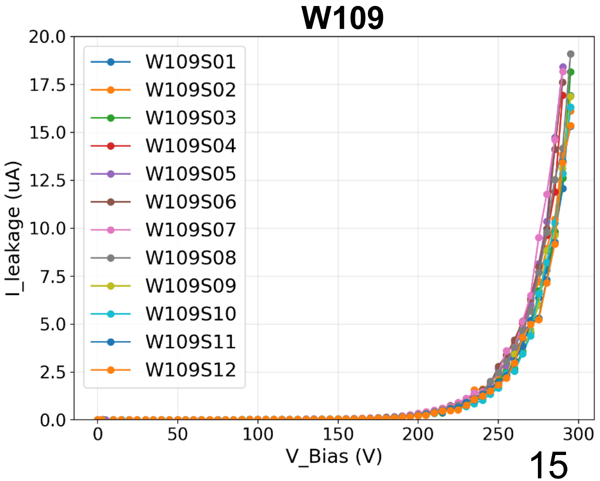

w106s03/04/05/06/07/08/09/10/11 mounted on 9-chip prototype module



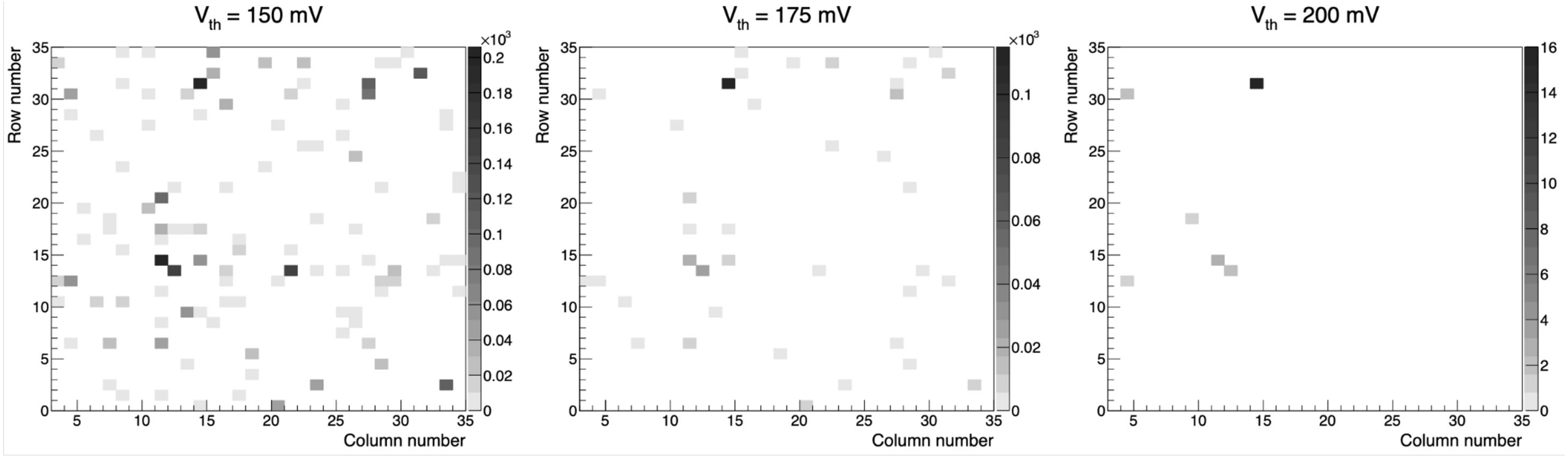



# Demonstration of Performance

## Bench Test: Noise Study on AstroPix v3

- Determine the percentage of pixels that are sensitive to the dynamic range and record intrinsic noise rates (plots below show 5s of noise scans)
- Threshold values of 200 mV (<=10 keV) are well below the AstroPix dynamic range floor of 25 keV
- Less than 0.5% of pixels have a noise rate > 2 Hz for data collection and are masked




- Active pixels: 96.2%
- 43/1,120 pixels disabled

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

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

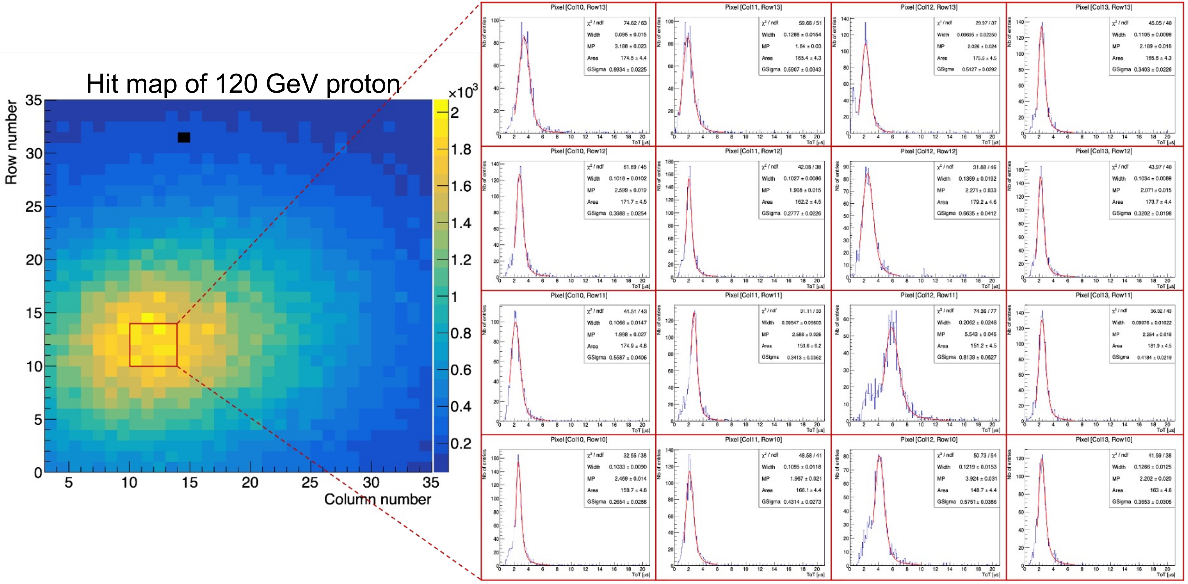
Fulfills BIC requirements on low energy threshold (25 keV tested in simulations), and provides primary estimate of QC yield of masked pixels.

# Demonstration of Performance

## Beam Test of AstroPix v3

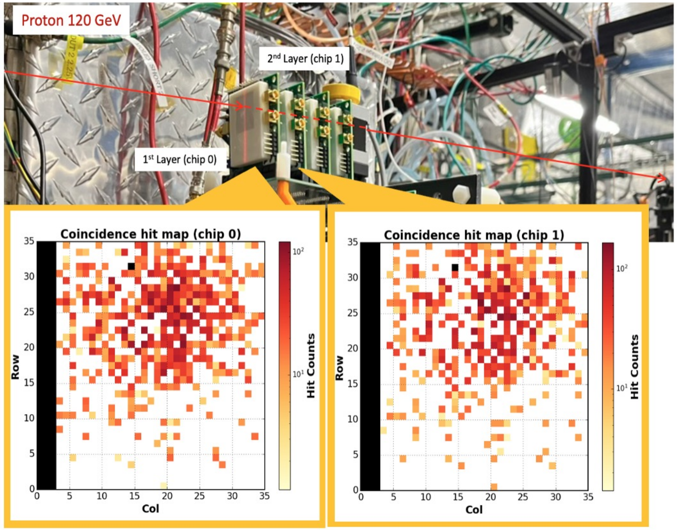
**Single layer**

- Data collected with a 120 GeV proton beam.
- The hit map reveals the proton beam profile with 500 µm position resolution.
- Histograms of collected ToT values for the marked pixels with MIP response.
- The beam was delivered in 4.2s-long spills every minute, with about 55K particles per spill, resulting in a delivered particle rate of around 13 kHz per spill.




**Double layer**

- 120 GeV proton beam events from the first two layers, read in coincidence, showing the position of the hit pixel.
- The **proof-of-concept demonstration of the integration of two daisy-chained AstroPix v3 layers in a beam-like environment**



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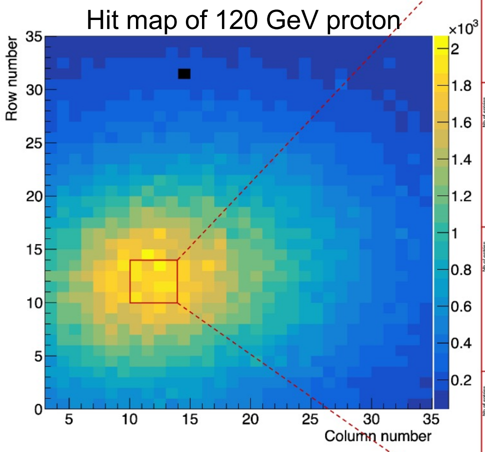
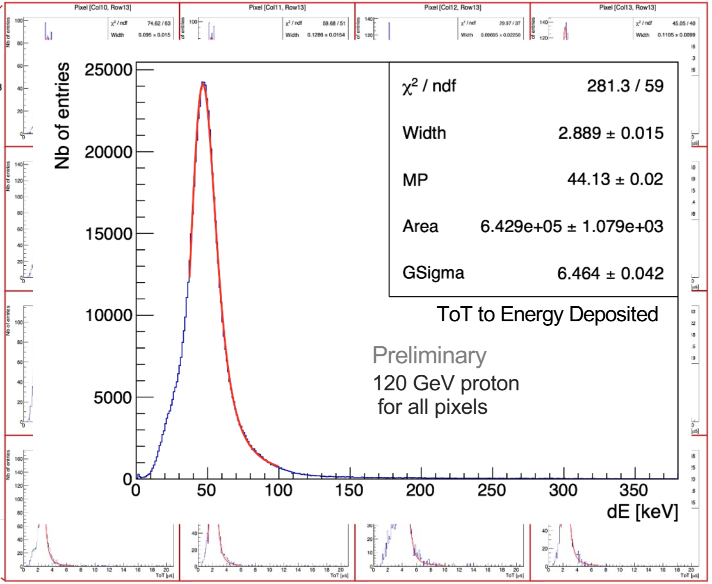
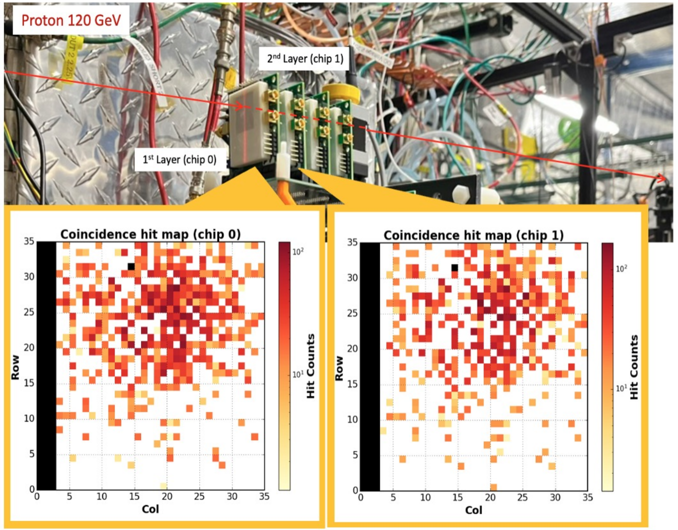
- The beam was delivered in 4.2s-long spills every minute, with about 55K particles per spill, resulting in a delivered particle rate of around 13 kHz per spill.




**Double layer**

- 120 GeV proton beam events from the first two layers, read in coincidence, showing the position of the hit pixel.
- The **proof-of-concept demonstration of the integration of two daisy-chained AstroPix v3 layers in a beam-like environment**

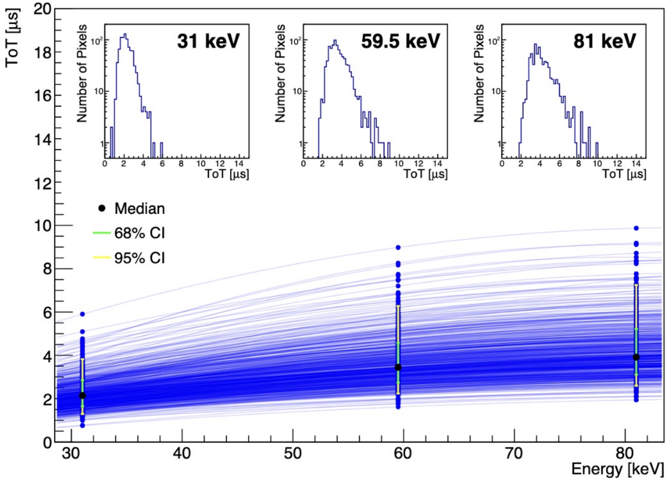


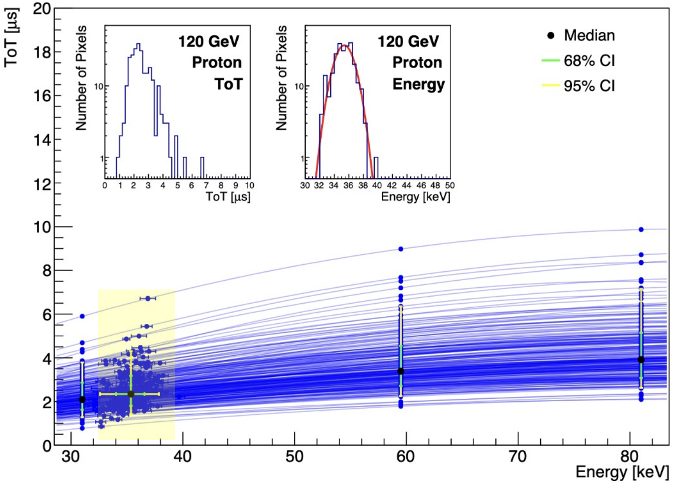
# Demonstration of Performance

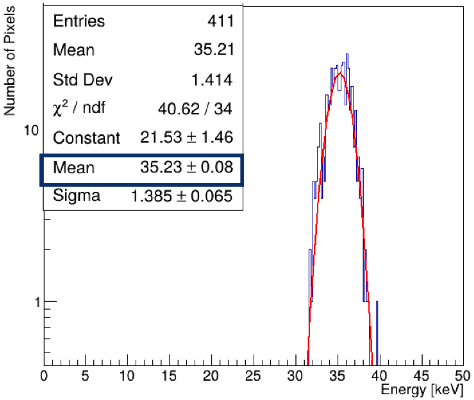
## Beam Test of AstroPix v3

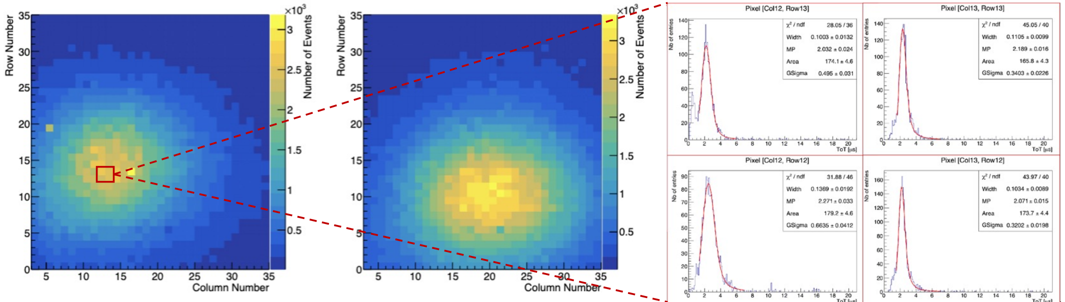
- Energy calibration with different energy sources for all pixels
- Observed 35.23 keV peak for MIP, fits well within calibrated dynamic range (25 keV - 200 keV) for AstroPix v3

  → The corresponding depletion depth: $132.4^{+4.8}_{-4.9}$ µm (Paper in preparation)

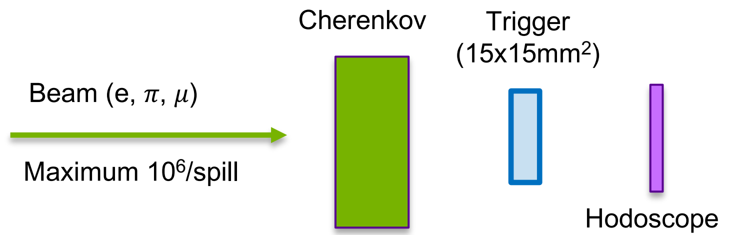


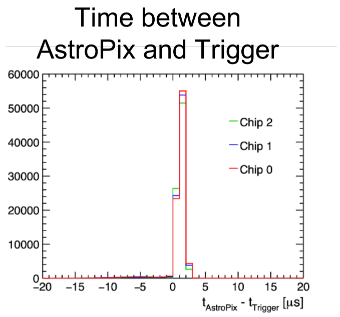



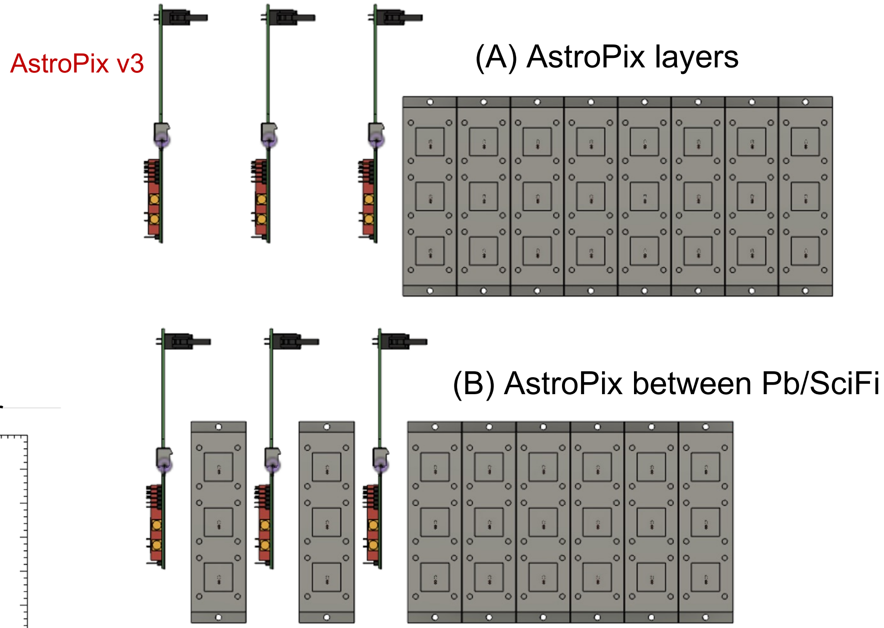



# Recent beam test at CERN PS T10 in July 2025





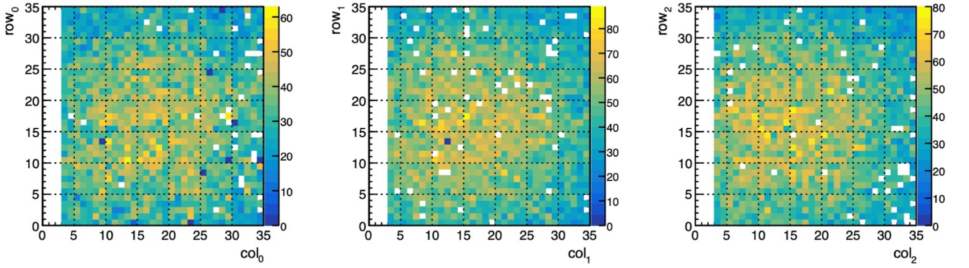


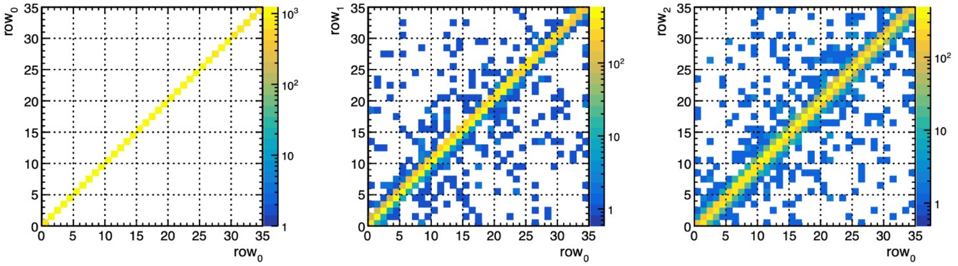

Goal: Proof-of-principle imaging of electrons and pions using a synchronized setup of AstroPix in the beam environment, using synchronized data taking between AstroPix and Pb/SciFi

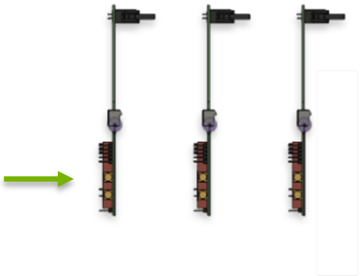
# Synchronization of three layers of AstroPix v3

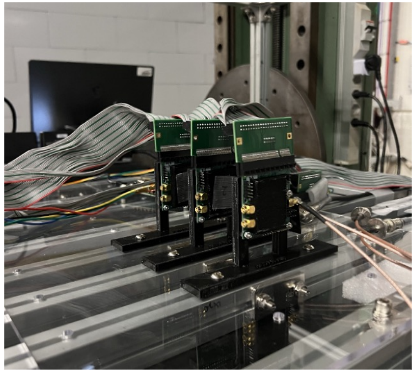
Hitmap




Correlation to the upstream chip

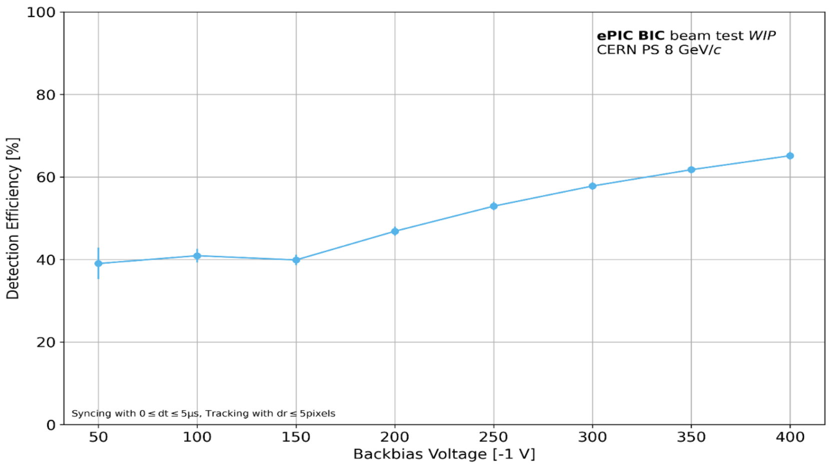


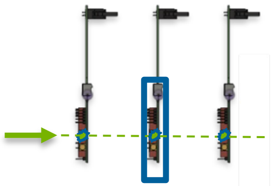


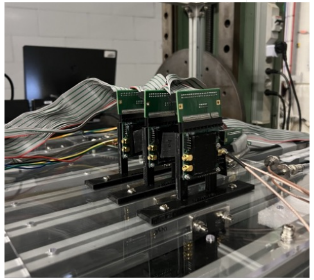
- Three AstroPix v3 layers are tested using the electron/pion beam at CERN PS.
- Correlations to the upstream show good alignment and data synchronization between AstroPix.
- The integrated system works well at a 2.7 kHz trigger rate on the beam. (BIC rate < 1 kHz/chip)

# AstroPix v3 chip tracking efficiency (Shallow depletion depth)




Detection efficiency in percentage as a function of bias voltage

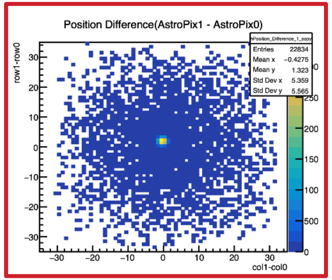




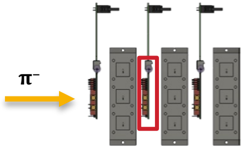
- Proof-of-principle for a method to measure tracking efficiency of AstroPix v3 under beam conditions.
- It is calculated as the probability of having a hit on the position estimated from hits on the first & third chips.
- The shallow depletion of v3 was known and is addressed in v5 with increased depletion.

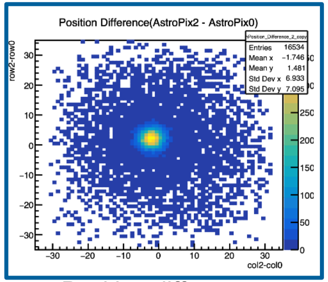
# Different shower profiles of electrons and pions

## Pions

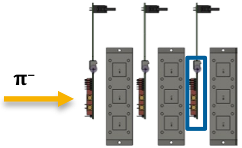



Position difference between 1st-2nd layer

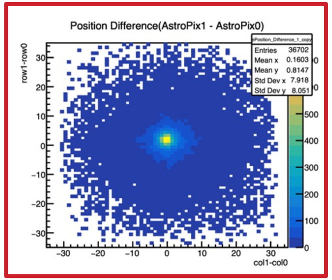


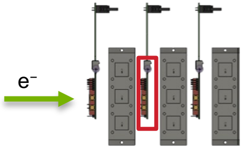

Position difference between 1st-3rd layer

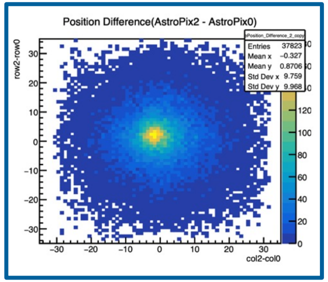



## Electrons

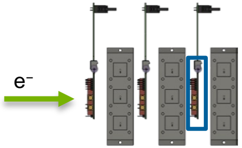


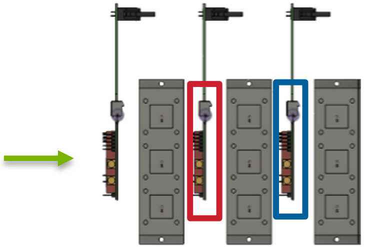

Position difference between 1st-2nd layer

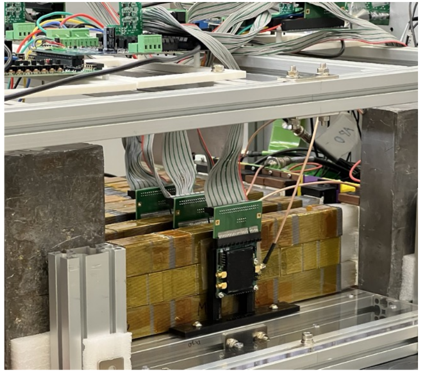



Position difference between 1st-3rd layer

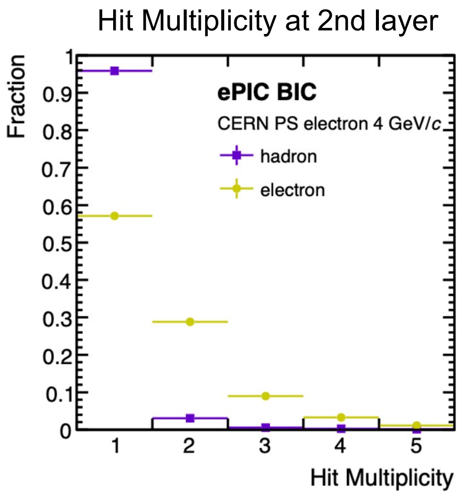


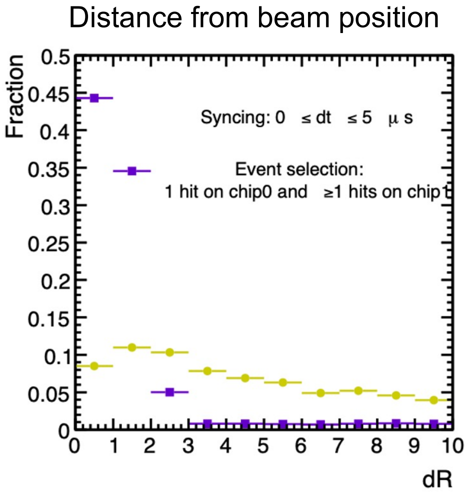



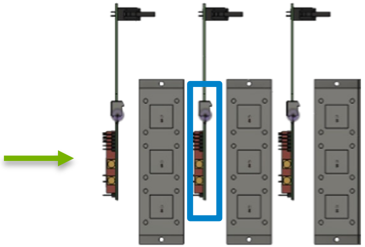


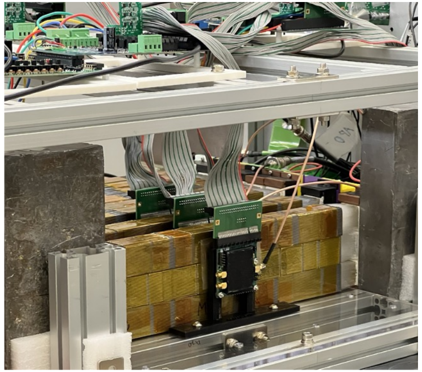
Proof-of-principle imaging of electrons and pions was performed using a synchronized AstroPix setup in the beam environment.

# Different shower profiles of electrons and pions



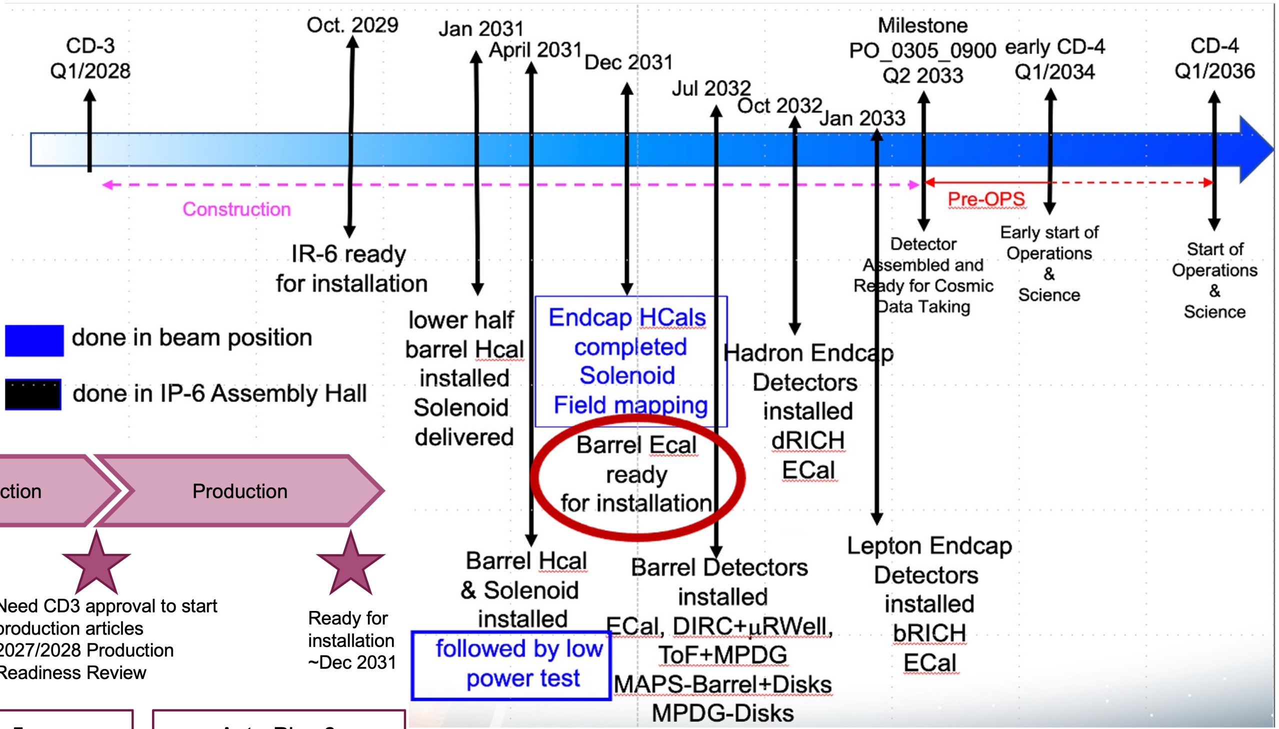





- The hit multiplicity and distance from the beam position at the second AstroPix v3 chip differ for electrons and pions.
- The electron/pion separation power in the beam test condition will be enhanced by AstroPix information on shower shape.

# ePIC Schedule




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

- Preliminary Design Review
  Sept 2025
- Final Design Review
  Goal: Late 2026
- Need CD3 approval to start production articles
  2027/2028 Production Readiness Review
- Ready for installation
  ~Dec 2031

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

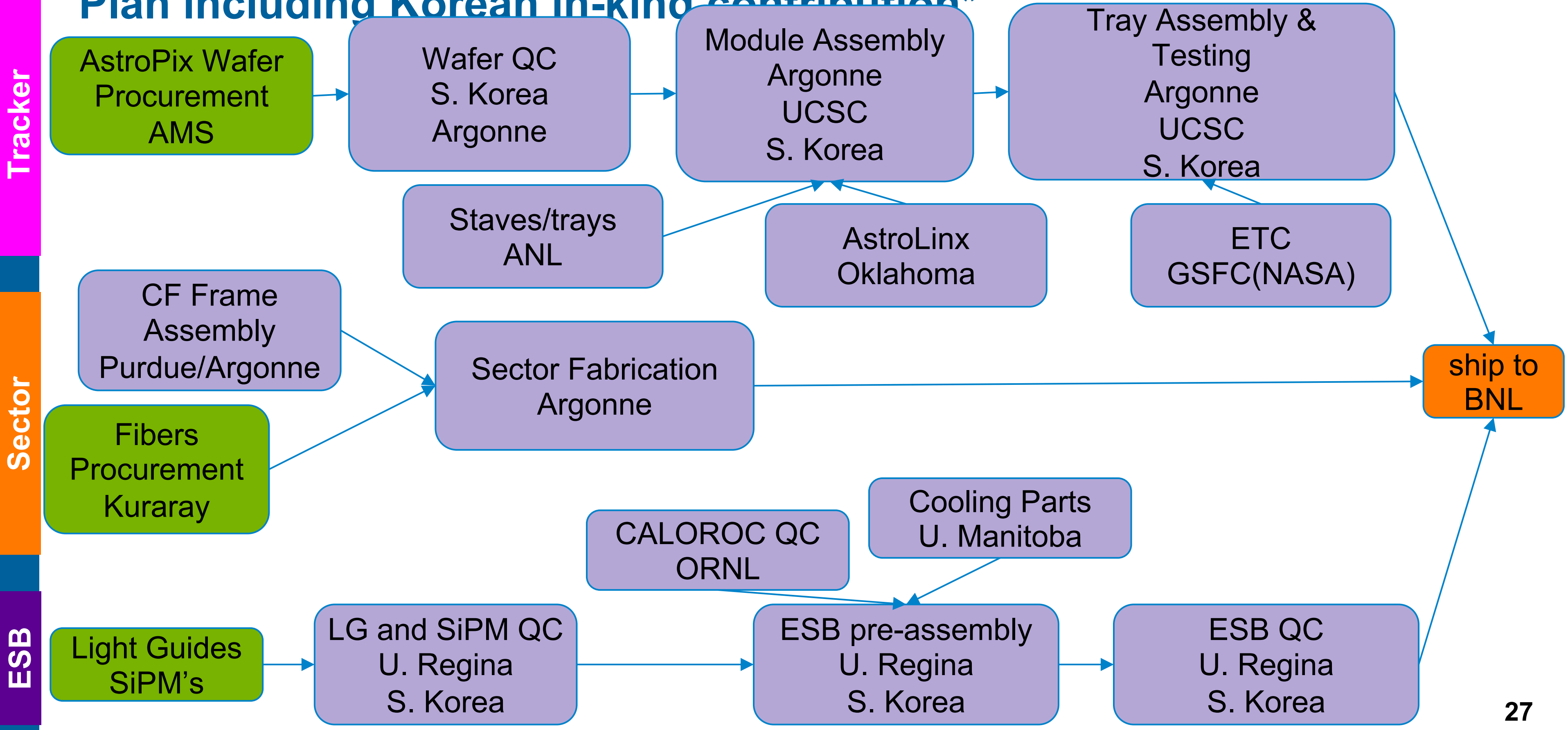
- AstroPix v5
- One full sector
- Final designs (90%)
- Production style procedures
- AstroPix v6 validation tests

- AstroPix v6
- 48 sectors

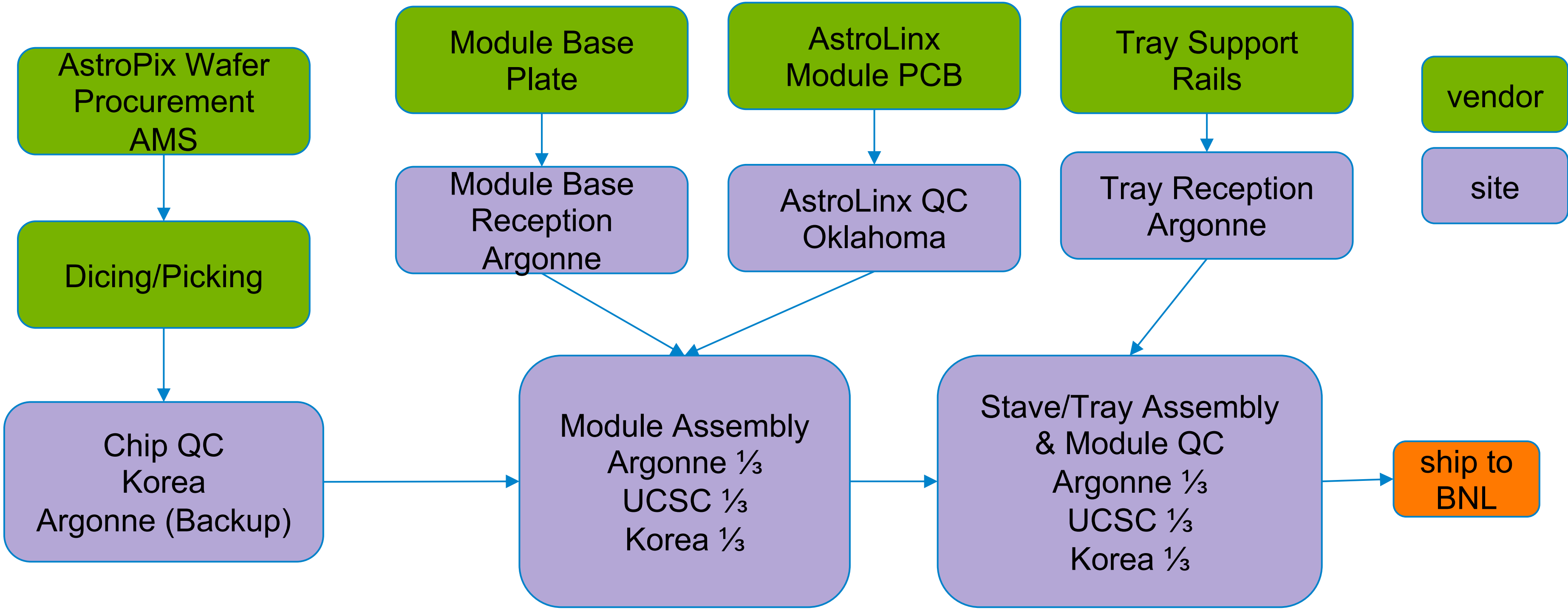
# Backup

# Production Plan


## Plan including Korean in-kind contribution*



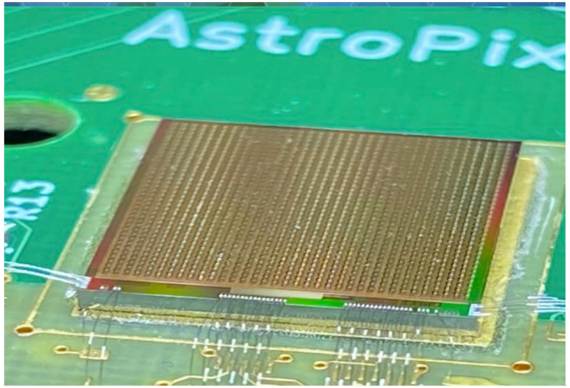
# Workflow: Tracker Layers




- 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

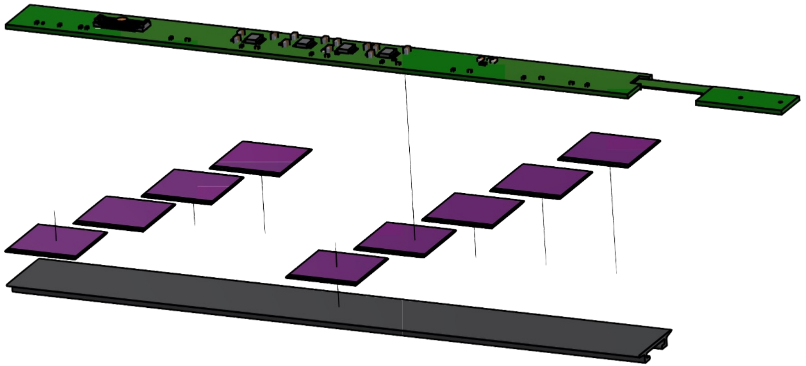



→Expect to have a high yield after chip testing until glued on a module

| 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)



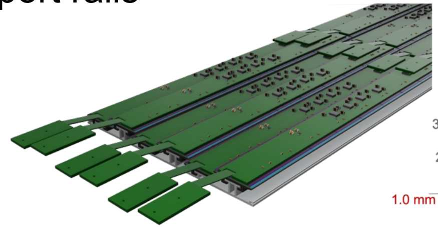
| **Module Assembly** | **# parts** | **# per batch** | **# batches** | **hours/batch** | **minutes/piece** | **# people** | **Total Person hours** | **Inactive hours/batch** | **Batches/week/production line** | **# of production lines** | **Total production weeks** | **Total production years (w/ 85% 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 |

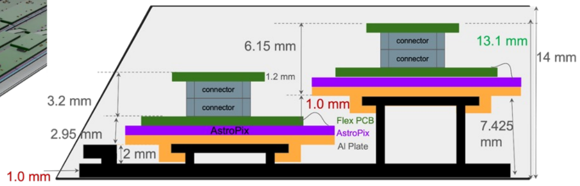
# Stave/Tray Assembly

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 |