AstroPix Module Interfaces Documentation

ePIC Barrel ECAL Project

Abstract

This document provides a technical description of the interfaces between AstroPix Module, Stave, and End-of-Stave FPGA board.

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Distribution List

History of Changes

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Contents

1 Introduction

The Barrel Electromagnetic Calorimeter comprises two detector technologies: AstroPix, an HV-CMOS MAPS sensor, and Pb/SciFi. The AstroPix sensors are integrated into 4 barrel layers, sandwich between Pb/SciFi layers to construct an imaging part of the barrel ECAL.

The document will provide details on the AstroPix chip, Module design, Module electric schematic, Stave assembly, and interfacing with the end-of-stave FPGA card.

2 AstroPix Chip Specification

AstroPix is a low-power HV-CMOS monolithic active pixel sensor designed with 180 nm CMOS process technology. The AstroPix baseline performance requirements are listed in table 1, comprising effective area, angular resolution, and energy resolution.

Pixel size	500 × 500 μm^2
Chip size	2 × 2 cm^2
Power usage	1.5 mW/cm^2
Dynamic range	20keV -700 keV
Energy resolution	5 keV σ @ 122 keV
Time resolution	25 ns
Noise Floor	5 keV
Signal threshold	20 keV

Table 1: The expected specifications of AstroPix readouts.

2.1 AstroPix Version 5

Currently testing AstroPix versions 3 and 4. The specifications of versions 3 and 4 will be added later. Version 5 is under design process and will be available at the beginning of FY2025. The specifications of AstroPix version 5 are listed in table 2.

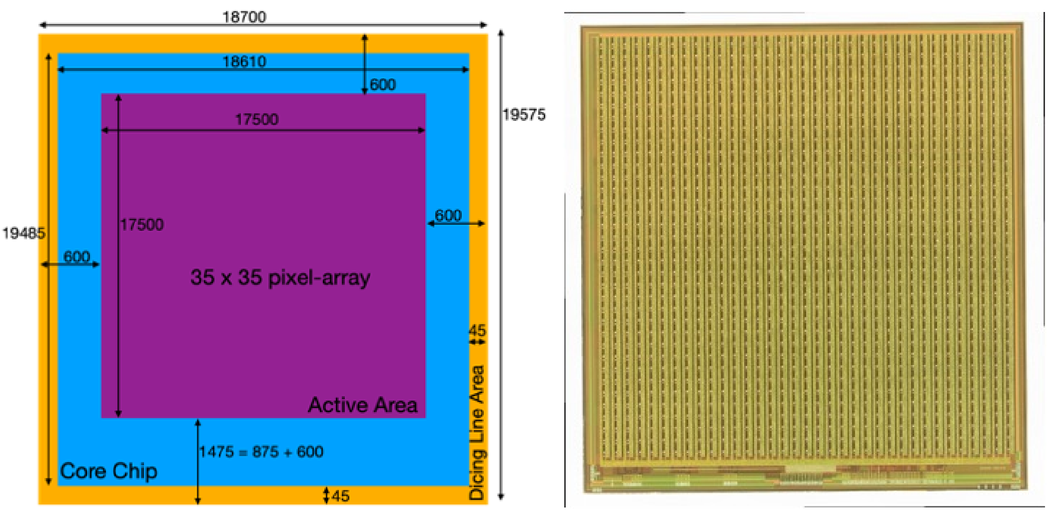

Figure 1: The AstroPix version 3 dimensions (left) and chip image (right). Version 5 dimensions match to the dimensions of version 3.

Pixel Pitch	500 μm (pixel size 300 μm)
Chip size	1.87 $\times$ 1.96 cm^2
Pixel matrix	35 $\times$ 33
Sensor thickness	525 μm
Power usage	1.63 mW/cm^2
Dynamic range	20keV -700 keV
Energy resolution	5 keV σ @ 122 keV
Time resolution	3.25 ns (25 ns without TDC)
Noise Floor	5 keV
Signal threshold	20 keV
Operating temperature (not tested)	-40 °C/+150 °C

Table 2: The specifications of AstroPix version 5.

Analog VDDA	1.8V
Analog VSSA	1.2V
Digital VDDD	1.8V
Analog Ground	GNDA
Digital Ground	GNDD
Sensor Reverse Bias Voltage	0 to 400V

Table 3: External supply voltage required of AstroPix version 5.

2.2 Digital Interface

AstroPix version 5 has pixel-by-pixel readout with 1 Hitbuffer assigned per pixel. Each column has an end-of-column buffer. There are 3 timestamp clocks: 15-bit course TimeStamp at 2.5 MHz, 3-bit fine TimeStamp at 20 MHz, and 16-bit flash TDC, which provides time response and Time-Over-Threshold resolution of 3.125 ns.

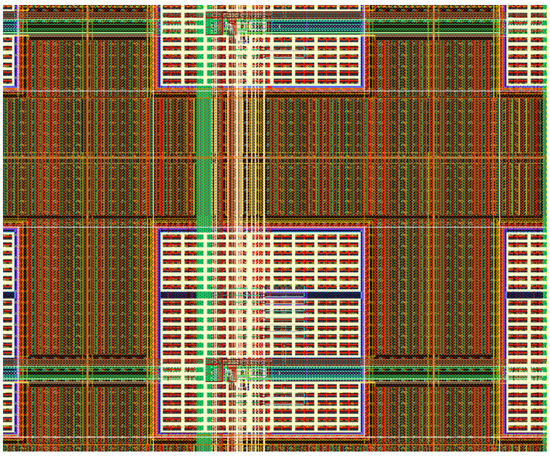

Figure 2: The pixel matrix structure for AstroPix with a pixel pitch of 500 μm and pixel nwell/implant size of 300 μm.

The comparator output is connected to Hitbuffer in the periphery. At the signal's first (falling) edge, coarse and fine TS are saved, and the Flash TDC is started. The TDC measures the exact difference from the falling edge to the next rising edge of the FineTS clk.

DaisyChain Protocol

The data streaming from End-of-tray-card (EOTC) to AstroPix and AstroPix to EOTC features a Header and Data format. The formats are different in two directions: EOTC to the chip (Module) configures AstroPix chips by writing data and AstroPix chip (Module) to EOTC only defines frames of data passing through the daisy chain with length. The command set is framed by the chip selection, some of the commands can be chained.

EOTC to Chip protocol:

bits

7	6	5	4	3	2	1	0
Command			Chip Address				

BIT	FIELD	DESCRIPTION
[4:0]	Address	Requires 20 single addresses - 0x00 - 0x14 : Single addresses - 0x15 - 0x1F : Reserved - 0x1D: Invalid - 0x1E: Broadcast
[7:5]	Command	8 Commands: - 0x01 - NOCMD / IDLE - 0x02 - Routing: dispatch addresses - 0x03 - Shift Register Config

IDLE Byte represents no specific command and an invalid address: 0x1D for address and 0x1 for IDLE -> **0x3D**

Figure 3: Hyder Bytes.

COMMAND	NAME	LENGTH	DESCRIPTION
0x01	NOCMD	1 Byte	Nothing to do
0x02	Address Config	1 Byte	Header Address represents the new address of the Chip Chip forwards command to the next chip with Address = Address + 1 To configure Addresses with first Chip “00”, send 0x40 to the first Chip, then send some IDLE bytes so that the Clock stays active and the addressing byte gets passed down the chain
0x03	Shift Register Config	N Bytes	Once this command is send, the whole SPI Frame is used - SPI Chip Select must be deasserted and reasserted to send a new command

Figure 4: Commands to AstroPix Chip.

Chip to EOTC protocol:

bits

7	6	5	4	3	2	1	0
Chip Address					Payload Length		

- Chip Address is the Configured Chip ID using the routing byte
- The PayloadLength is the number of bytes trailing the header

Hit Packet Type

At the moment we only need 1 Packet type:

bytes

0	1	2	3	4	5	6	7
Header	Row<0:5>,Col<0:1>	Col<2:5>,TSFromDet<0:3>	TSFromDet<4:11>	TSFromDet<12:14>,TSFromDet2<0:4>	TSFromDet2<5:12>	TSFromDet2<13::14>,TSFine<0:2>,TSFine<0:2>	TSTDC1<0:3>, TSTDC2<0:3>

Figure 5: Data Format from the Chip.

AstroPix version 5 will have 1x8 Bytes. Right now, they can be reduced by on-chip subtraction. As shown in figure 5 the data bytes can be decoded as,

8b Header,
6b Row,
6b Col,
15b TS,
15b + 2x(4b + 3b) ToT.

2.3 Digitization Data Rate

The whole Chip triggers at 10Hz. Only one counter per row/column with 8 Bytes. With Chip array of 36 $\times$ 36 and 500 μm Pixels there are around 1300 Pixels.
1300 * 8 Bytes Data = 10400 Bytes
Protocol including daisy chain etc.. = 50% overhead i.e. +5200 Bytes
Total = 15600 Bytes /s / chip
Pixelator: 1 Chip, Full Module with 9 chips = 9 * Pixelator = 9 Chips
For one Module: 9 $\times$ 15600 = 140 kByte/s

The maximum expected rate for Barrel Ecal using the following table 4:
Avg hit rate/pixel [1/s] is 5.68E-02, so for a chip it is 70 hits and for a Module it is 840
Considering double the hits per module, it is 1680
The expected data rate for a Module is 1680*8 bytes = 13.44 kBytes/s.

Data rate for Barrel ECAL

Integration time [s]	6.00E-06
Nb of pixels	5.28E+08
Total rate [1/s]	3.00E+07
Avg hit rate/pixel [1/s]	5.68E-02
Propablility of getting hit twice	1.94E-08
Propablility of getting hit twice for entire detector	1.02E+01
Drop rate for the entire detector	3.41E-07
Nb of hits with one drop	2.93E+06

Table 4: Data hit rate

The expected hit rate for all imaging layers together Low rates is well below < 30 MHz
This translates to a maximum hit rate per tracker stave (1 x 108) $<$ 36 kHz

This draft will also add more information about module design, electrical interface and power numbers. This information can temporarily be accessed at link here

2.4 AstroPix Chip Final Dimensions

Final size of the AstroPix chip reticle will be 2 cm $\times$ 2 cm. It will have pixel-by-pixel flash-TDC to provide fast time response with individual tune-DAC for the pixel tuning. Table 5 provide details of physical dimensions of AstroPix chip considered for the imaging layers of Barrel Electromagnetic Calorimeter at the ePIC.

Final chip size	2 cm $\times$ 2 cm^2
Pixel Pitch	500 μm (pixel size 300 μm)
Pixel matrix	39 $\times$ 37
Sensor thickness	525 μm
Dicing line clearance	45 μm
Pixel to chip edge distance	205 μm

Table 5: Physical dimensions of final AstroPix chip.

This dimension provides full coverage along the stave length spanning the length of 218.16 using 12 modules with 9 chips each. The current AstroPix dimension is shorter than final dimensions and hence requires a design respin after version 5 has been tested.

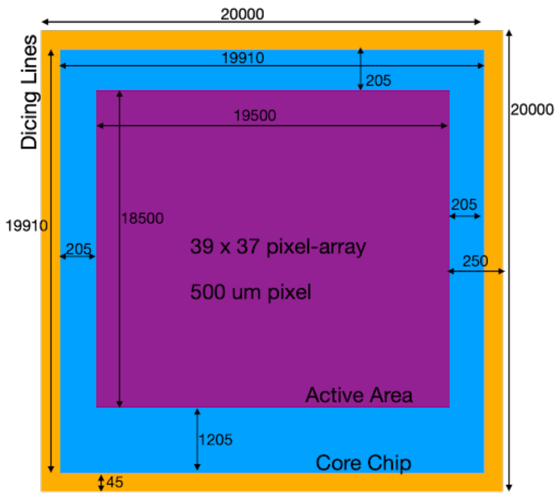

Figure 6: The AstroPix final dimensions.

Each module will have 9 chips with intermediate gap of 200 μm. The module length is 18.11 cm with full stave length is 218.16 cm. The number of chips and modules are calculated by following consideration,

Total BIC length = 440 cm
Length to cover with single stave = 220 cm
AstroPix size + gap = 2.02 cm
Number of chips required = 220/2.02 = 108.91
Round of number for required chips = 108 chips/stave
Which leads to 9 chips and 12 modules

The next section will describe Mechanical considerations of the module and stave designs.

3 Mechanical Structure Design

Imaging part of calorimetry has 4 layers of low-power HV-CMOS MAPS sensors, AstroPix. Layer numbers 1, 3, 4, and 6 will be integrated with AstroPix chips

3.1 Total Active Area Calculations

In this section the active area on the Tray (along the length and width) is calculated.

Along the Tray length

Along the stave we have 2 cm AstroPix chip with in between gap of 0.02 cm. The active length on the chip is 1.95 cm (39 pixels).

Active chip array length = 1.95 cm
Inactive area on chip = 0.05 cm
Inactive area in-between the chips = 0.02 cm
Active area percentage = Active area / Total detector area = 1.95/2.02 = 96.53Inactive area percentage = 0.07/2.02 = 3.47

Along the Tray width

In this direction Chip and Module will have considerable inactive area. The calculation below provides numbers to minimize the dead area in this direction.
In addition to it Module have total inactive area of 5 mm. The Modules can be flipped to minimize the inactive area to 2 mm near the sidewalls

Active chip array length = 1.85 cm
Inactive area on top side = 0.025 cm
Inactive area on bottom side (digital petiphery) = 0.125 cm
Total inactive area on chip = 0.15 cm
Inactive area on the Module at top of the chip = 0.02 cm
Inactive area on the Module at the bottom of the chip = 0.03 cm (wire-bonds)

Unavoidable dead area at top = Dead area on the (Chip + Module) = 0.025 + 0.2 cm.
Total unavoidable dead area = 0.45 cm. (Keeping top side outward on each sidewall)

There will be 4 Imaging layers in the Barrel Electromagnetic Calorimeter (BIC). Appendix xx provides design geometry for the BIC Sector.

Available space for imaging layers is,
Layer 1: 107.257 mm = 10.7257 cm
Layer 3: 117.411 mm = 11.7411 cm
Layer 4: 122.488 mm = 12.2488 cm
Layer 6: 132.642 mm = 13.2642 cm

Here two options are considered, 1. without leaving any space at sidewalls for support structure, 2. considering 1 mm of inactive area at the sidewalls for the support structure.

The calculation shows number of staves required to cover the entire width of the Tray with the active bulk of the detector and total dead area in each layer.

Option 1: Zero space at the sidewalls

Layer 1: 10.7257 cm
Number of Staves = (10.7257-0.45)/1.85 = 10.2757/1.85 = 5.554 → **6 Staves**
Total active length available = 1.85*6 = 11.1 cm
Additional **overlap** needed to fit 6 Chips (in addition to 1.25 mm at bottom and 0.25 at top) = 11.1 - 10.2757 = 0.8243 cm
Additional overlap per Stave = 0.8243/6 = 0.1374 cm = 1.374 mm

Total dead area percentage = 0.45/10.7257 = 4.2%

Layer 3: 11.7411 cm
Number of Staves = (11.7411-0.45)/1.85 = 11.2911/1.85 = 6.1033 → **6 Staves**
Total active length available = 1.85*6 = 11.1 cm
Additional **dead** space = 11.2911 - 11.1 = 0.1911 cm
Additional dead area per Stave = 0.1911/6 = 0.03185 cm = 0.319 mm

Total dead area percentage = (0.1911+0.45)/11.7411 = 5.46%

Layer 4: 12.2488 cm
Number of Staves = (12.2488-0.45)/1.85 = 11.7988/1.85 = 6.3777 → **6 or 7 Staves?**

- 6 Staves:
Total active length can be available = 1.85*6 = 11.1 cm
Additional **dead** space = 11.7988 - 11.1 = 0.6988 cm
Additional dead area per Stave = 0.6988/6 = 0.1165 cm = 1.165 mm

Total dead area percentage = (0.6988+0.45)/12.2488 = 9.38%

- 7 Staves:
Total active length can be available = 1.85*7 = 12.95 cm
Additional **overlap** needed to fit 7 Chips = 12.95 - 11.7988 = 1.1512 cm
Additional overlap per Stave = 1.1512/7 = 0.16446 cm = 1.645 mm

Total dead area percentage = 0.45/12.2488 = 3.67%

Layer 6: 13.2642 cm
Number of Staves = (13.2642-0.45)/1.85 = 12.8142/1.85 = 6.9266 → **7 Staves**
Total active length available = 1.85*7 = 12.95 cm
Additional **overlap** needed to fit 7 Chips = 12.95 - 12.8142 = 0.1358 cm
Additional overlap per Stave = 0.1358/7 = 0.0194 cm = 0.194 mm

Total dead area percentage = 0.45/13.2642 = 3.39%

Option 2: 1 mm space at the sidewalls

Layer 1: 10.7257 cm
Number of Staves = (10.7257-0.05-0.6)/1.85 = 10.0757/1.85 = 5.446 → **6 Staves**
Total active length available = 1.85*6 = 11.1 cm
Additional **overlap** needed to fit 6 Chips (in addition to 1.25 mm at bottom and 0.25 at top) = 11.1 - 10.0757 = 1.0243 cm
Additional overlap per Stave =1.0243/6 = 0.1707 cm = 1.707 mm

Total dead area percentage = 0.65/10.7257 = 6.06%

Layer 3: 11.7411 cm
Number of Staves = (11.7411-0.65)/1.85 = 11.0911/1.85 = 5.995 → **6 Staves**
Total active length available = 1.85*6 = 11.1 cm
Additional **overlap** needed to fit 6 Chips = 11.1 - 11.0911 = 0.0089
Additional overlap per Stave = 0.0089/6 = 0.0015 cm = 0.015 mm

Total dead area percentage = 0.65/11.7411 = 5.54%

Layer 4: 12.2488 cm

Number of Staves = (12.2488-0.65)/1.85 = 11.5988/1.85 = 6.2696 → **6 or 7 Staves?**

- 6 Staves:

Total active length can be available = 1.85*6 = 11.1 cm

Additional **dead** space = 11.5988 - 11.1 = 0.4988 cm

Additional dead area per Stave = 0.4988/6 = 0.0831 cm = 0.831 mm

Total dead area percentage = (0.4988+0.65)/12.2488 = 9.38%

- 7 Staves:

Total active length can be available = 1.85*7 = 12.95 cm

Additional **overlap** needed to fit 7 Chips = 12.95 - 11.5988 = 1.3512 cm

Additional overlap per Stave = 1.3512/7 = 0.1930 cm = 1.93 mm

Total dead area percentage = 0.65/12.2488 = 5.31%

Layer 6: 13.2642 cm

Number of Staves = (13.2642-0.65)/1.85 = 12.6142/1.85 = 6.8185 → **7 Staves**

Total active length available = 1.85*7 = 12.95 cm

Additional **overlap** needed to fit 7 Chips = 12.95 - 12.6142 = 0.3358 cm

Additional overlap per Stave = 0.3358/7 = 0.04797 cm = 0.4797 mm

Total dead area percentage = 0.65/13.2642 = 4.9%

Table 6: Summary of AstroPix coverage.

Layer#	Length (cm)	No. of Staves	dead (cm)		Overlap (cm)		Dead Area (%)	
			2 mm	3 mm	2 mm	3 mm	2 mm	3 mm
1	10.7257	6	-	-	0.8243	1.0243	4.2	6.06
3	11.7411	6	0.1911	-	-	0.0089	5.46	5.54
4	12.2488	6	0.6988	0.4988	-	-	9.38	9.38
		7	-	-	1.1512	1.3512	3.67	5.31
6	13.2642	7	-	-	0.1358	0.3358	3.39	4.9

Table 7: Summary of AstroPix coverage with 2 mm gap at sidewall.

Layers	Length (cm)	No. of Staves	dead (cm)	Overlap (cm)	Total Dead Area (%)
1	10.7257	6	-	0.8243	4.2
3	11.7411	6	0.1911	-	5.46
4	12.2488	6	0.6988	-	9.38
		7	-	1.1512	3.67
6	13.2642	7	-	0.1358	3.39

Table 8: Summary of AstroPix coverage with 3 mm gap at sidewall.

Layers	Length (cm)	No. of Staves	dead (cm)	Overlap (cm)	Total Dead Area (%)
1	10.7257	6	-	1.0243	6.06
3	11.7411	6	-	0.0089	5.54
4	12.2488	6	0.4988	-	9.38
		7	-	1.3512	5.31
6	13.2642	7	-	0.3358	4.9

4 Electrical Interfaces

A Appendix