Development of Readout Electronics for a High-speed Event-driven Neutron Imaging Detector Based on Timepix4

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SNS

中国科学院大学
University of Chinese Academy of Sciences

medipix collaboration

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Backgrounds

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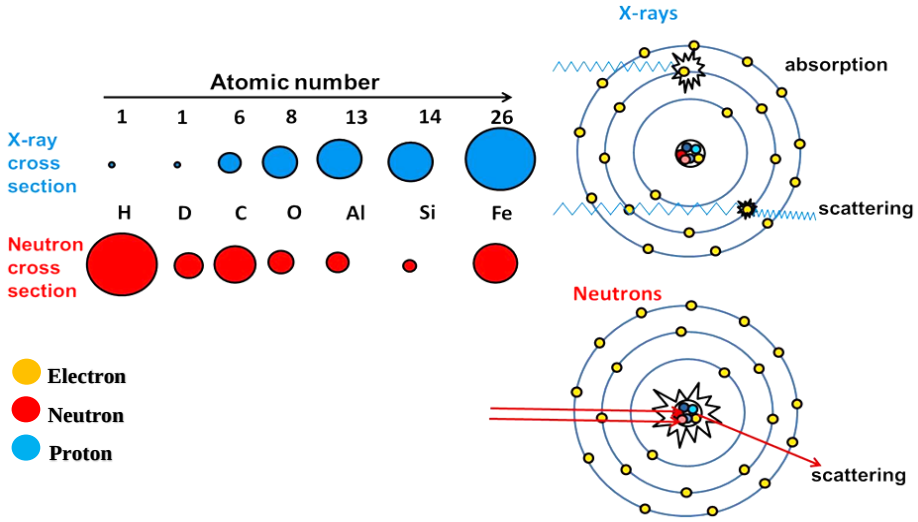
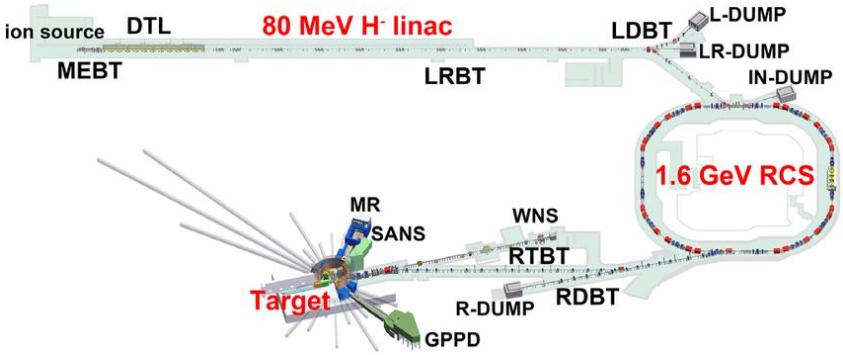
1. China Spallation Neutron Source (CSNS)

➢ Higher Flux and Higher Energy Neutrons Based on Accelerators



CSNS Aerial View



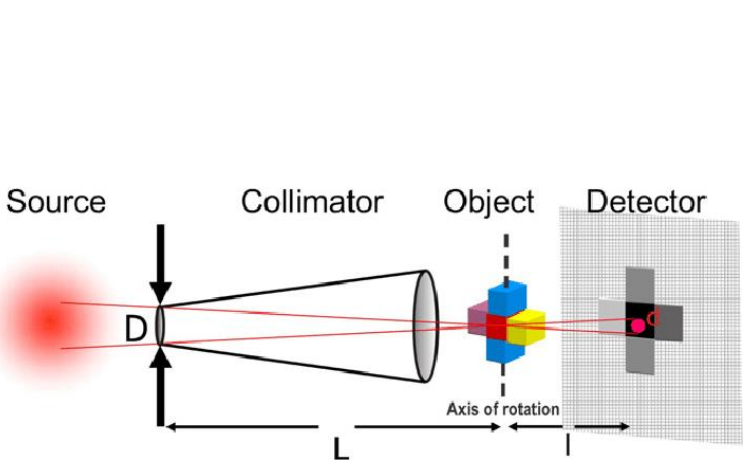
CSNS Schematic Diagram

Neutrons vs. X-rays	
X-rays	Neutrons
● Electromagnetic Interaction, Reacts with Extra-Nuclear Electrons ● High Flux	● Interacts with Atomic Nuclei ● Cross-Section Independent of Atomic Number ● Isotope Sensitivity ● Magnetic Moment

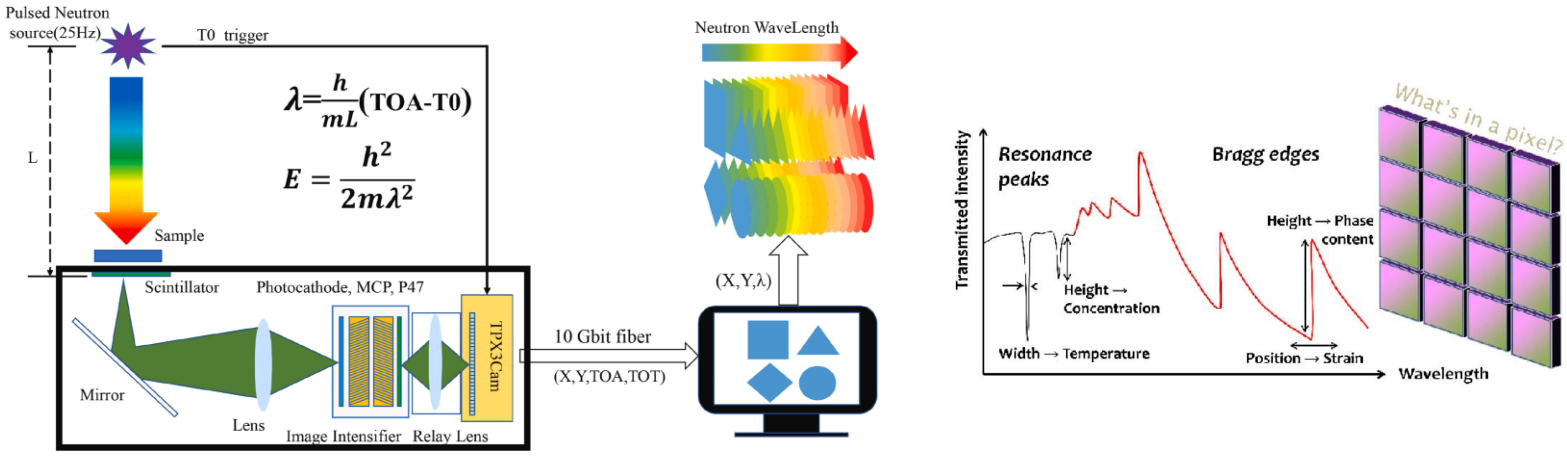
- **Parameters of the Neutron Source:**
- **Proton Bombardment Cycle:** 40ms(25Hz) **Proton Energy:** 1.6GeV
- **Target Material:** Tungsten **Number of Spectrometers (Total):** 20
- **Target Power:** 100KW (Phase I), 500KW (Phase II)

Backgrounds

2. Energy-resolved Neutron Imaging Based on Pulsed Neutrons



Typical neutron imaging



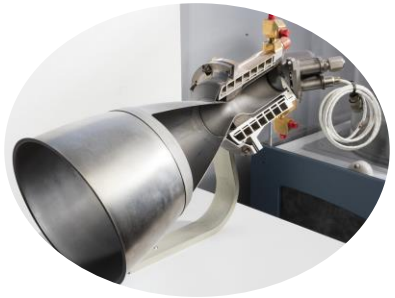
Principle of Energy-resolved Imaging Based on Pulsed Neutrons

➢ Wide Range of Applications:

Materials Science
(Strain in Train Wheel Axles)

Environmental Science

Renewable Energy

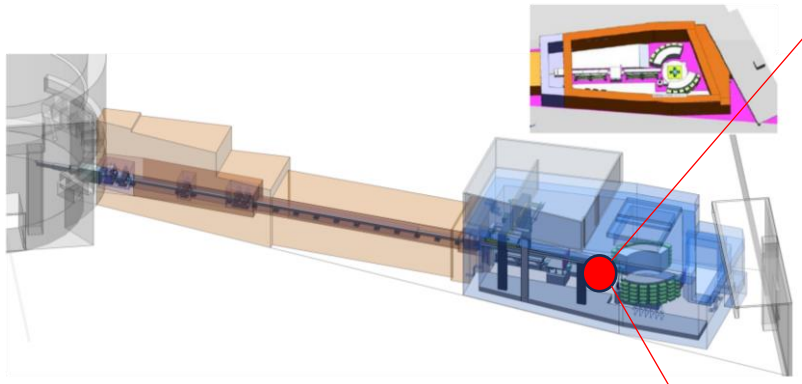


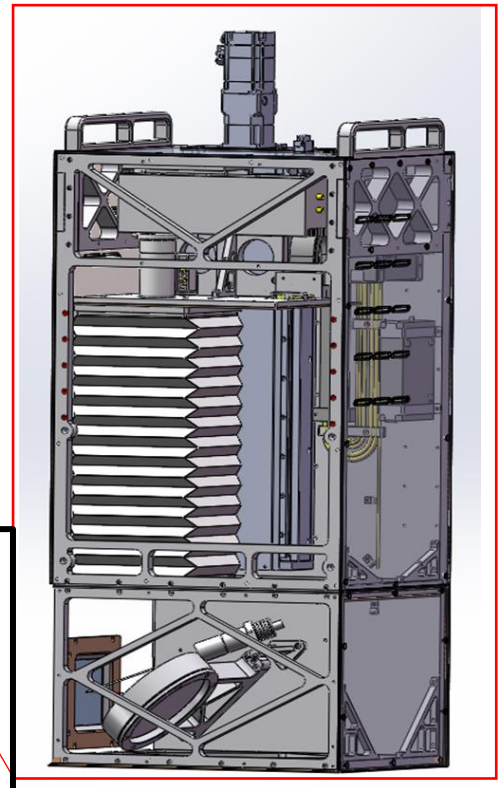
Aerospace and Automotive Industry

Archaeology and Cultural Heritage

Backgrounds

3. Energy-resolved Neutron Imaging Detector





Energy-resolved Neutron Imaging Spectrometer at CSNS

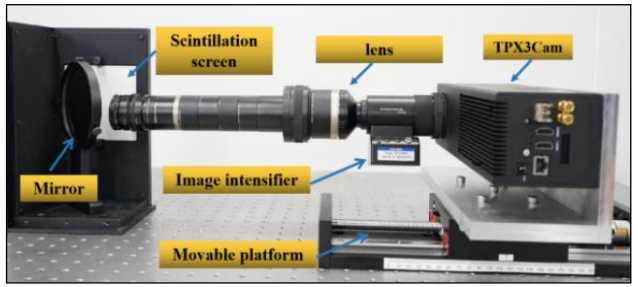
Instrument parameters		
General parameters	Moderator	Coupled hydrogen moderator
	Wavelength resolution	$\Delta\lambda/\lambda < 0.5\%$
	Flux at sample position	~10^7/n/s/cm^2
	L1 distance and ? λ	35m, 5.1Å@25Hz, 10.2 Å@12.5Hz
	L2 distance and ? λ	30m, 4.1Å@25Hz, 8.2 Å@12.5Hz
Imaging mode	FOV	200*200mm^2
	L/D	L:10m D:5,10,20,40,80mm L/D:2000,1000,500,250,125
	Best resolution	<50 um

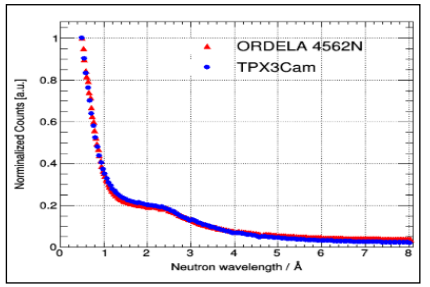
Beam Size:

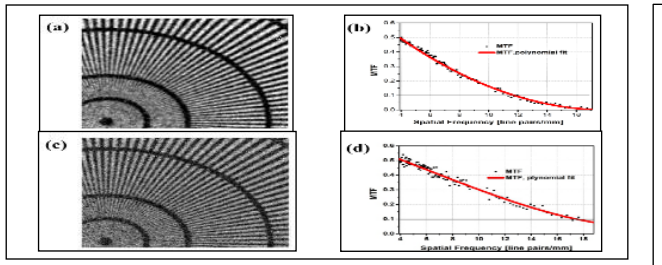
20 cm x 20 cm

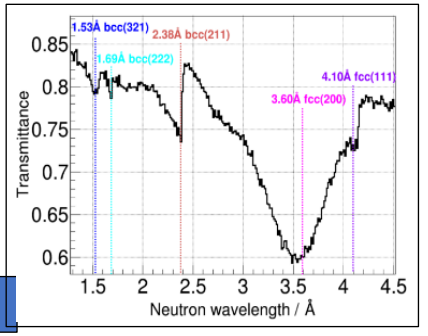
Flux: ~10^7 n/s/cm^2

- **High time resolution: <1us**
- **Wavelength resolution: ~ 1‰**
- **Spatial resolution: ~20um**









The latest results: 20 μm (25 lp/mm)

- **Future Goals:** Larger Area, Higher spatial resolution(<20 um), Higher time (energy) resolution(<1us)

- One Timepix3 chip
- Pixels:256x256
- Only 80Mhits/s

Higher event rate

Larger sensitive area

Timepix4 Camera

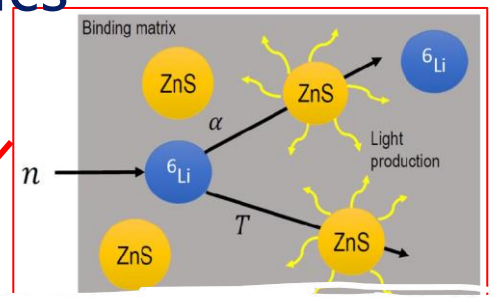
Contents

Readout Electronics

1. Challenges for readout electronics

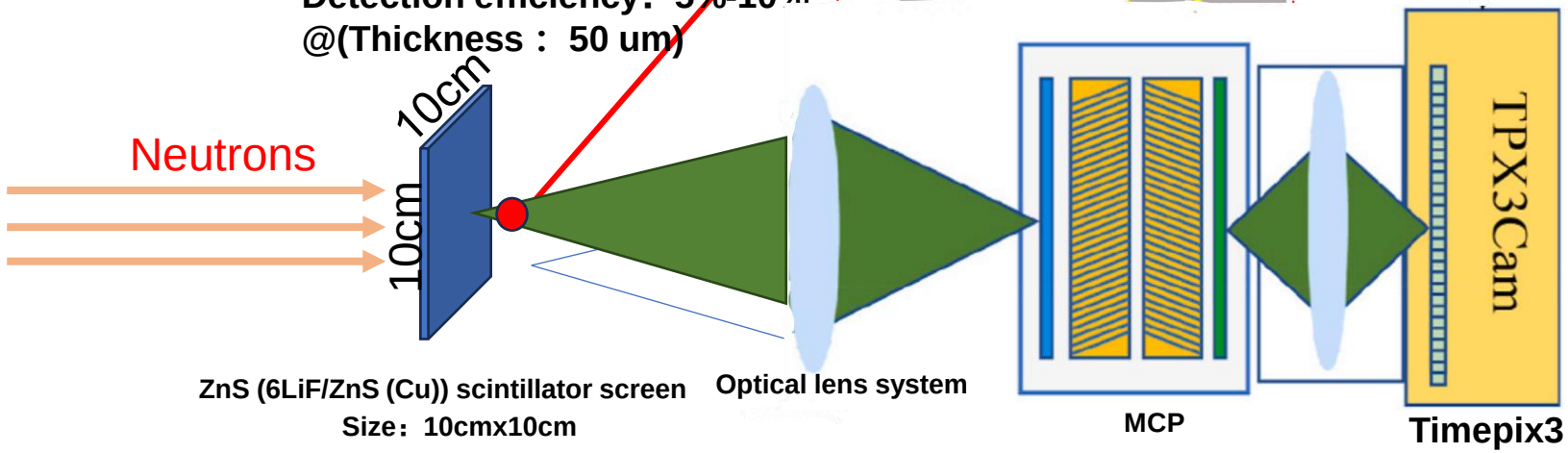
Beam Size：20 cm x 20 cm

Flux：~10^7 n/s/cm^2



- A neutron reaction produces ~10^5-10^6 photons
- Partial photon passed through the optical system, only max 100 hits were detected by Timepix3

Detection efficiency：5%-10%
@(Thickness： 50 um)



ZnS (6LiF/ZnS (Cu)) scintillator screen
Size：10cmx10cm

Optical lens system

MCP

Timepix3

Performance is limited by the event-driven camera

Max rate: 80Mhits/s

Neutrons Flux
~10^7 n/s/cm^2

scintillator screen size :10cmx10cm

Detection efficiency：5%-10% @(Thickness： 50 um)

10^7 n/s/cm^2 *(10cm x 10cm)*10%=10^8 n/s

max 100 hits/n

10^8 n/s *100hits/n=10^{10} hits/s

8 bytes /hit

$8*10^{10}$ bytes/s

It's worth noting that this estimate is based on the theoretical maximum

The readout data size is huge！！

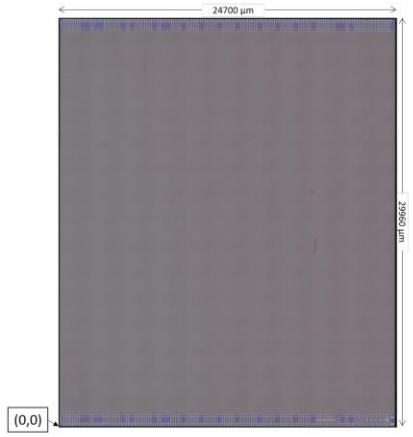
Readout Electronics

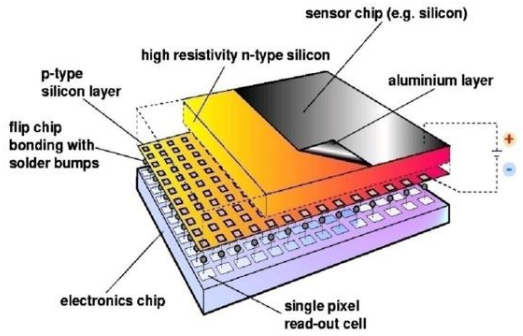
2. Why Timepix4?

Table 1 Parameters of several pixel chips

Name	Pixel Size(μm²)	Array size	Frame Rate (Hz)	nm	Operating mode
PILATUS3	172 × 172	60 × 97	500	250	Frame
Medipix3	55 × 55	256 × 256	1.5k	130	Frame
Timepix3	55 × 55	256 × 256	1.5k	250	Frame、Data-driven
XPAD3	130 × 130	80 × 120	700	250	Frame
UFXC32K	75 × 75	128 × 256	23k(@2bit)	130	Frame
BPIX3	55 × 55	88× 88	1.2K	130	Frame
Timepix4	55 x 55	512 x 448	80k	65	Frame、Data-driven

- Timepix series of chips is one of the most advanced chips that can meet the requirements for position and time measurement in energy-selective neutron imaging.





Hybrid pixel detector readout chip

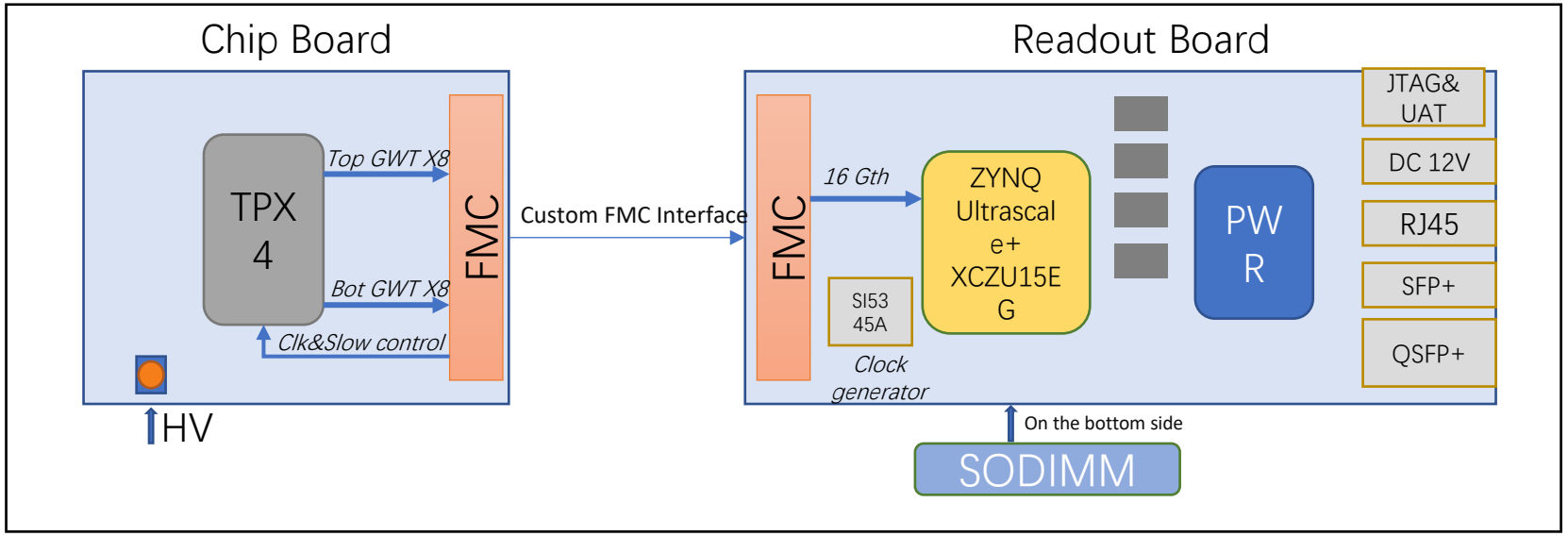
			Timepix3 (2013)	Timepix4 (2019/20)	
Technology			IBM 130 nm – 8 metal	TSMC 65 nm – 10 metal	
Pixel size			55 x 55 μm	55 x 55 μm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable (TSV) 512 x 448	3.5 x
Sensitive area			1.98 cm²	6.94 cm²	
Readout modes	Data driven (tracking)	Mode	ToT and TOA		
		Event packet	48-bit	64-bit	
		Max rate	< 43 Mhits/cm²/s	357.6 Mhits/cm²/s	8 x
		Pix rate equiv.	1.3 kHz/pix average	10.8 kHz/pix average	
	Frame Based (imaging)	Mode	Count: 10 bit + iToT	Count: 8 or 16 bit CRW	
		Frame	Zero suppressed (with pix addr)	Full frame (no pix addr)	
		Max count rate	82 Ghits/cm²/s	~ 800 Ghits/cm²/s	10 x
		Max frame rate	N/A (worst case: 0.8ms readout)	80 kHz CRW	
TOT energy resolution			< 2 keV	< 1 keV	2 x
Time resolution			1.56 ns	~ 200 ps	8 x
Readout bandwidth			≤ 5.12 Gbps (8 x 640 Mbps)	≤163.8 Gbps (16 x 10.2 Gbps)	32 x
Target minimum threshold			< 500 e⁻	< 500 e⁻	

Key parameters:

- **Readout**: Data-driven(X,Y,TOA)
- **Number of pixels**: 512 x 448 (230,000 pixels)
- **Time resolution**: ~200 ps
- **Maximum counting rate**: 357 MHz/cm2/s
- **Data readout**: 16 x 10 Gbps SERDES / chip
- **Power consumption**: 6 watts (~1W/cm2)
- **PCB connection:** WB (both sides), TSV (both sides + middle)

Readout Electronics

3. High-bandwidth Readout Electronics Hardware Architecture



Chip Board Key Specs

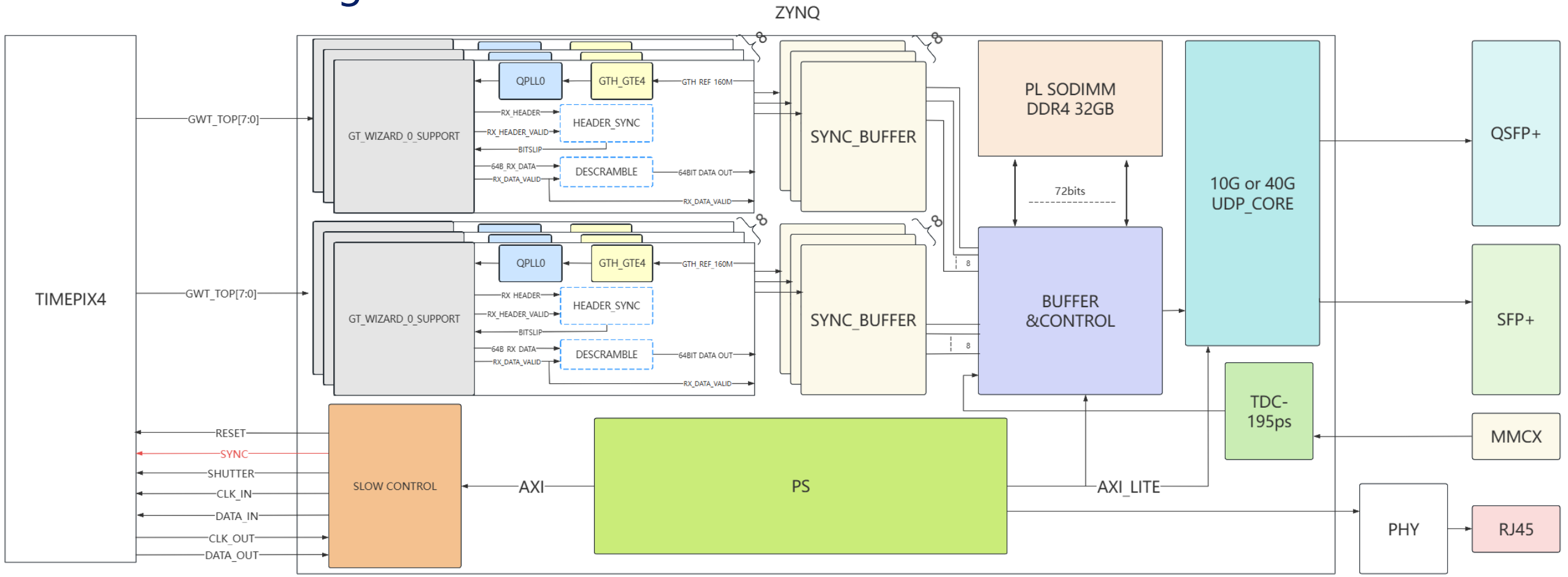
- Megtron6 High-speed PCB material
- 8 CM x 10 CM
- 16 x GWT connected to FMC
  - 8x TOP
  - 8x BOT(Swap P/N polarity)
- Temperature monitoring
- Integrated clock generator
  - Can be synchronized with the readout board
- Slow control
  - TOP side or Bottom side
  - I2C support

Readout Board Key Specs

- FPGA: Zynq Ultrascale+ 15EG
- Megtron6 High-speed PCB material
- DRAM:
  - PL: 32GB DDR4 SODIMM (2133 MHz)
  - PS: 4GB DDR4 Component
- Chip Board Interface: FMC HPC
  - 16 x 16.3 Gbps MGT
  - LVDS: 22 pairs (HP) 12 pairs (HD)
  - 2A@12V 4A@3.3V
- DAQ Interface:
  - RJ45: PS 1GbE
  - SFP+: up to 16Gbps
  - QSFP: up to 4 x 16 Gbps
- Slow Control: 1000M PS RJ45
- On board JTAG & UART
- On board TDC for T0 (195ps)

Readout Electronics

4. Firmware Design



- **Full bandwidth readout from a single Timepix4 chip to the readout board**(16X10.24G)
- **Two operating modes**: pass-through mode , on board DDR4 cache
- **DAQ readout** : 4X16Gbps @QSFP, 16Gbps @SFP+

Readout Electronics

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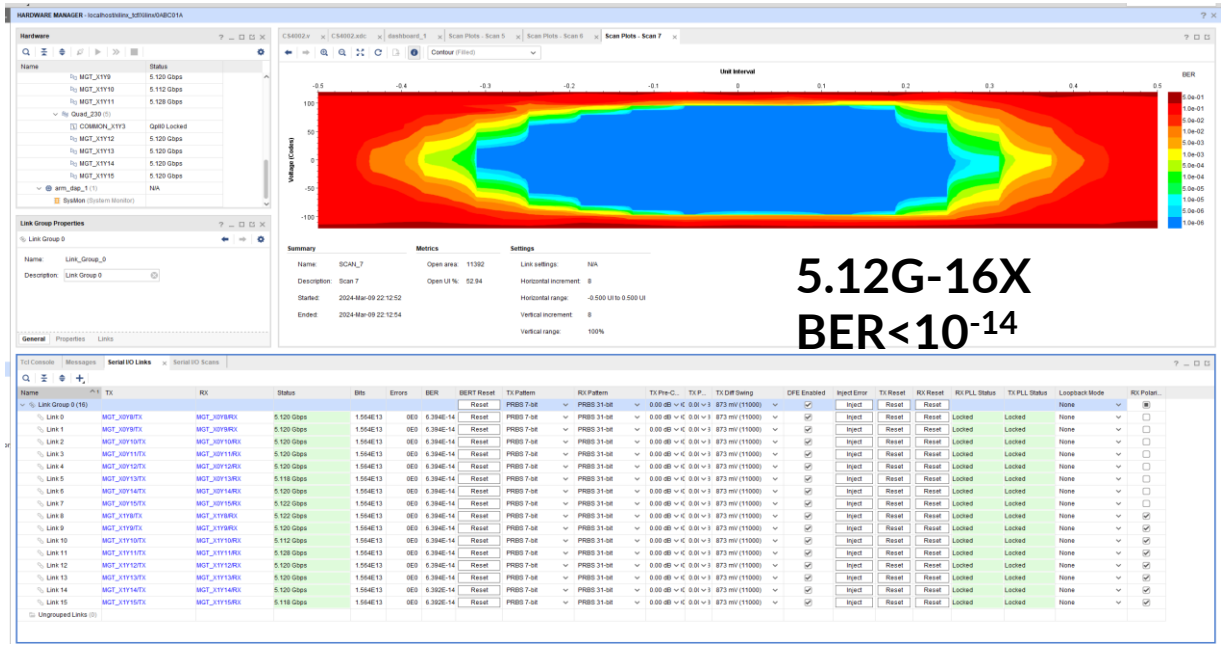
5. High-speed Links Tests

➢ GWT-5.12G(Timepix4 to Readout Board)

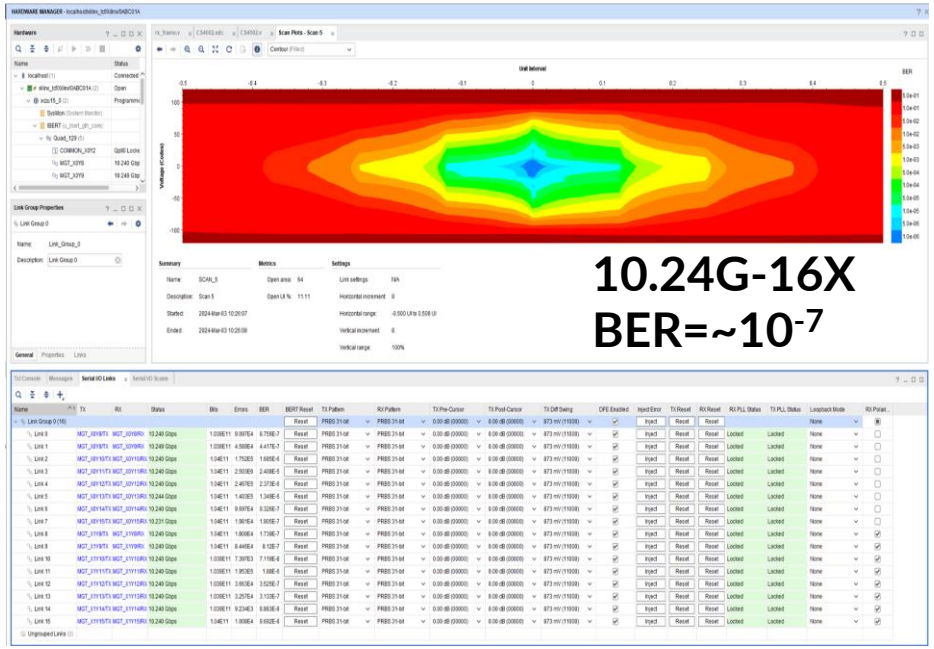


5.12G-16X
BER<10^{-14}

NO Errors (Some PLL_CC OFF)

PRBS-31 testing of the 16-channel GWT links@5.12G

➢ GWT-10.24G(Timepix4 to Readout Board)



10.24G-16X
BER=~10^{-7}

All links locked

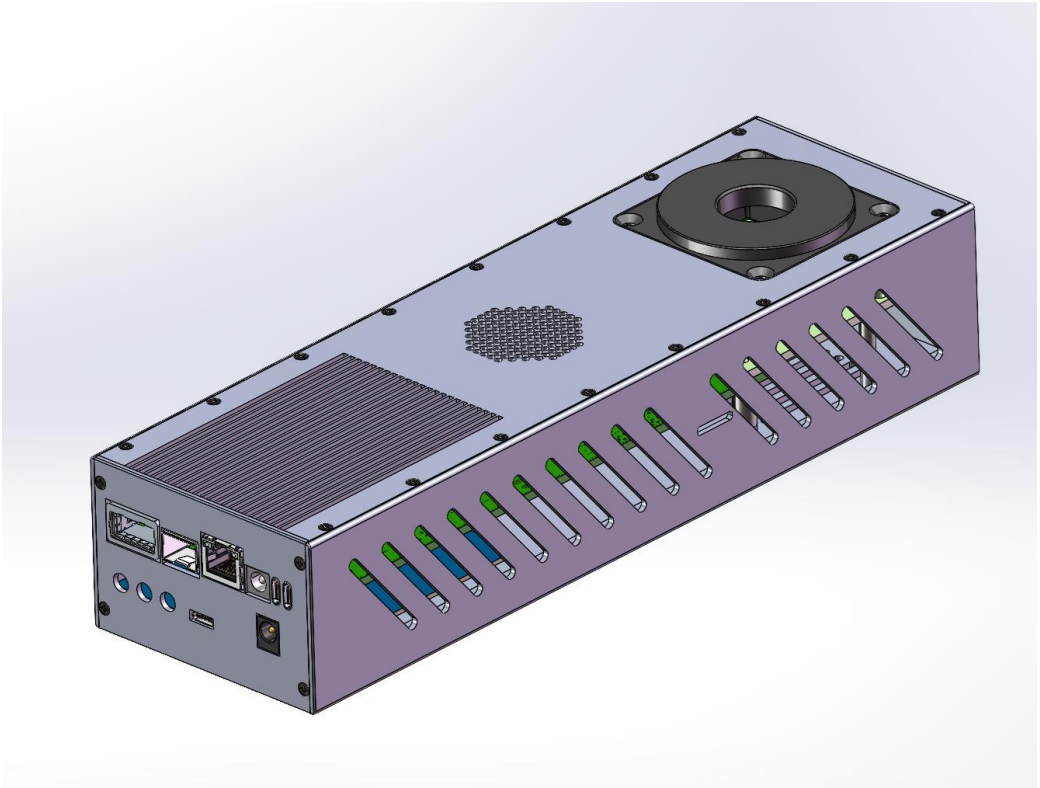
PRBS-31 testing of the 16-channel GWT links@10.24G

- A single Timepix4 chip achieves a maximum bandwidth of 80Gbps, reaching half of the maximum theoretical value.

Contents

Prototype of Camera

1. CTPX1 Data-driven Readout Camera Prototype



CTPX1 Camera

Table2 CTPX1 **VS.** ASI TPX3Cam

Parameters	ASI TPX3Cam	CSNS CTPX1	Note
Camera Size	288x80x90mm^3	300x90x60mm^3	
Sensitive Area	1.4 cm x 1.4 cm	2.97 cm x 2.49 cm	× 3.5
Pixel Array	256 x 256	512 x 448	× 3.5
Pixel Size	55 um	55 um	
Time resolution	1.6 ns	195 ps	× 5
DAQ Readout Bandwidth (max)	10GbE	40 GbE	× 4
Cache	?	DDR4(max 32GB)	
Maximum count rate	80 MHz	> 600M@40Gbps	
Camera Interface	C-mount	C-mount E-mount ...	

Prototype of Camera

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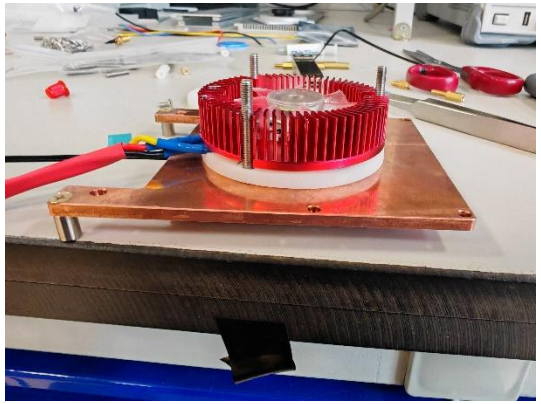
2. CTPX1Camera

CTPX1 Camera

CTPX1 Mechanical Housing

Chip Board with TPX4 300um Si

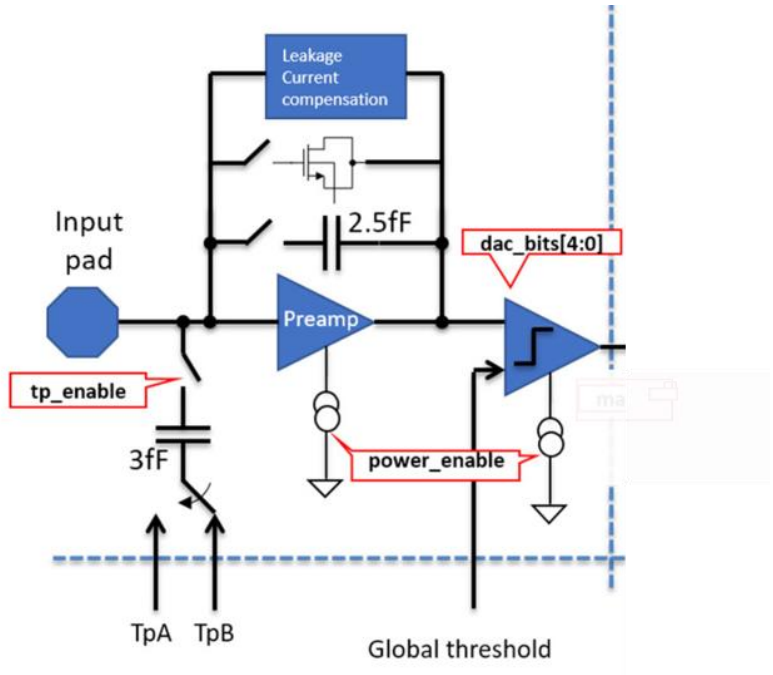


TEC Cooler

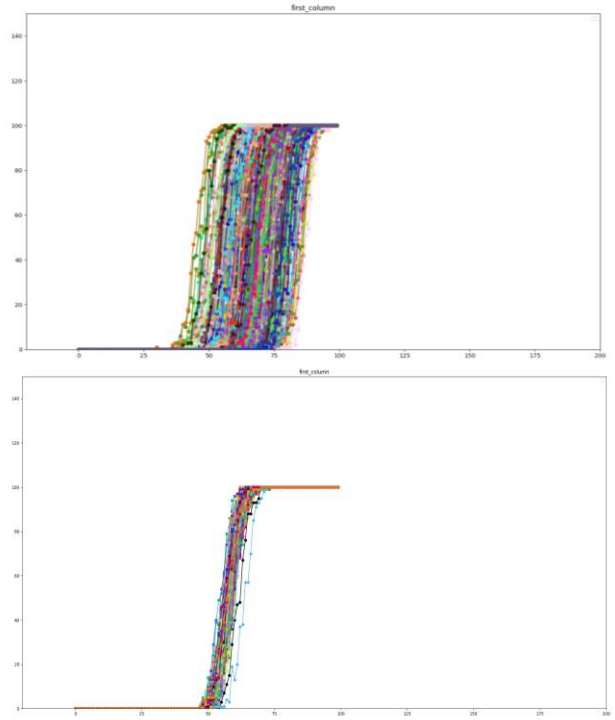
Readout Board

Prototype of Camera

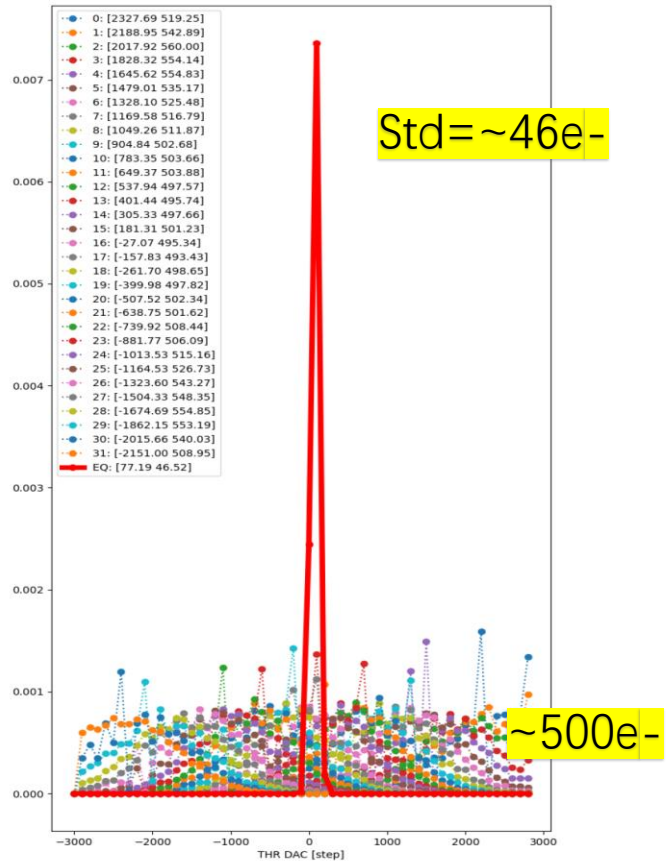
3. Timepix4 Equalization



Global threshold and local DAC[4:0]



Comparison of threshold before and after adjustment of Local DAC in the first column of pixels



Equalization

- Threshold Std for all pixels after Equalization is less than 50e-

Prototype of Camera

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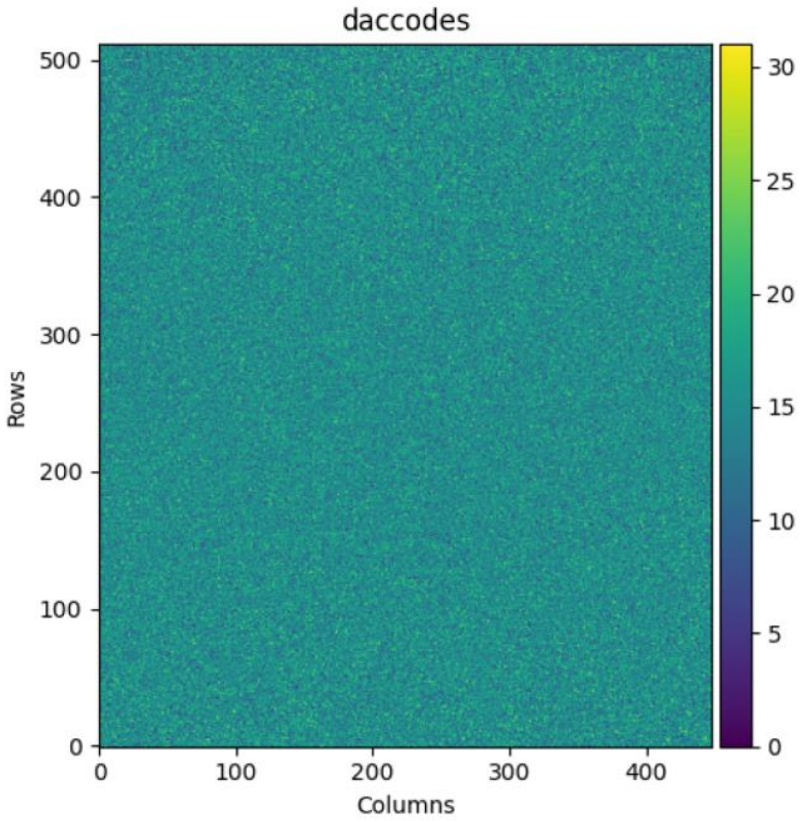
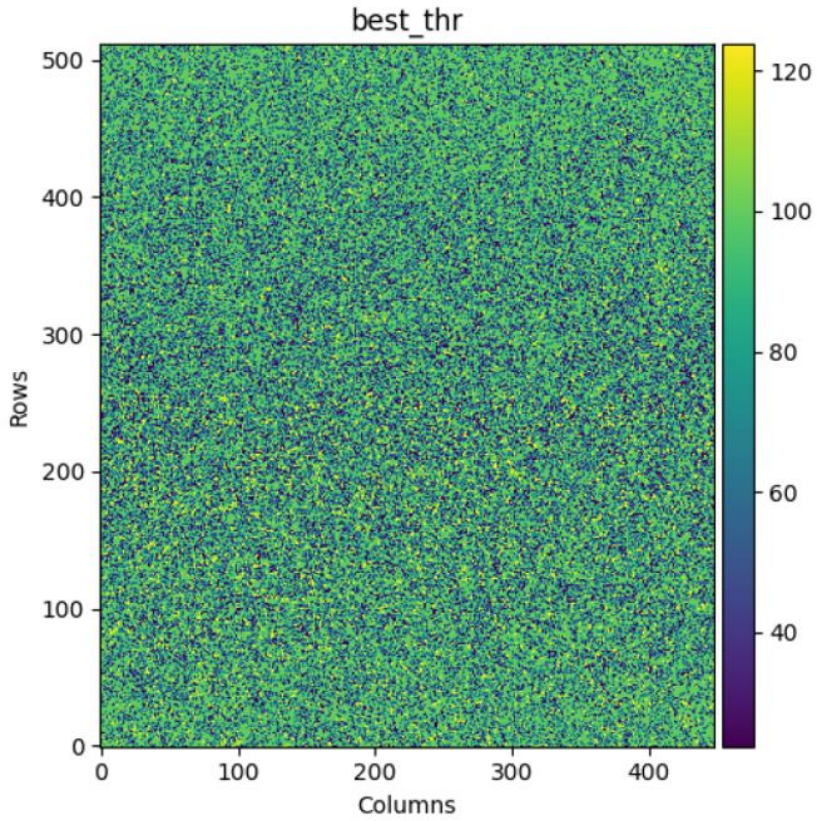
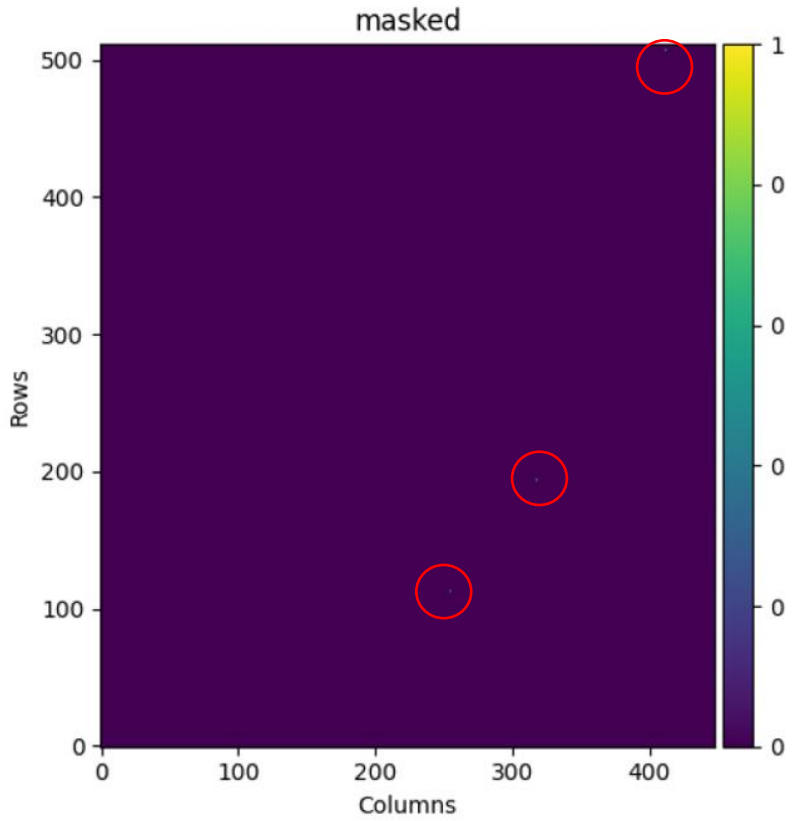
4. Timepix4 Equalization



Local DAC code



Threshold Distri. (e-)



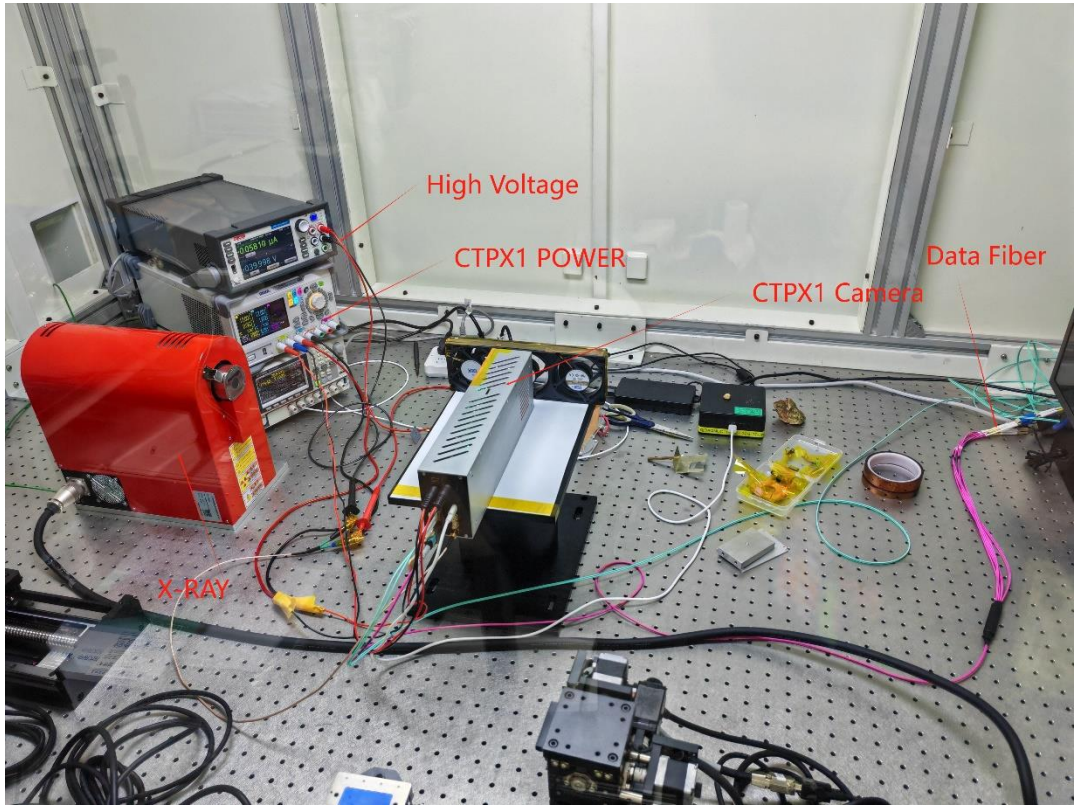
Masked Pixels

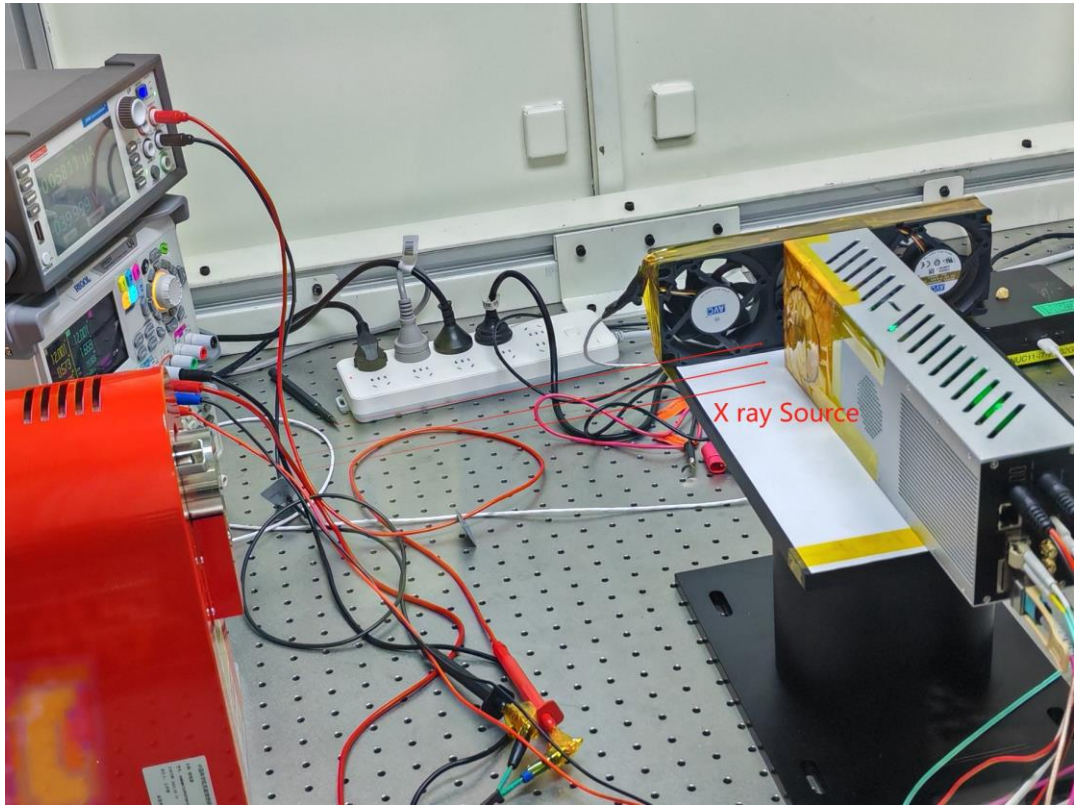
- Mask the pixels with threshold > 6.6σ from average, 3 pixels masked

Contents

Cosmic-ray & Radiation Source Test

1. Test environment





CTPX1 X-ray test Environment

- Timpix4 sensor Bias：40V
- Readout Links：2x2.56G + 10G UDP

Cosmic Ray and Alpha Test

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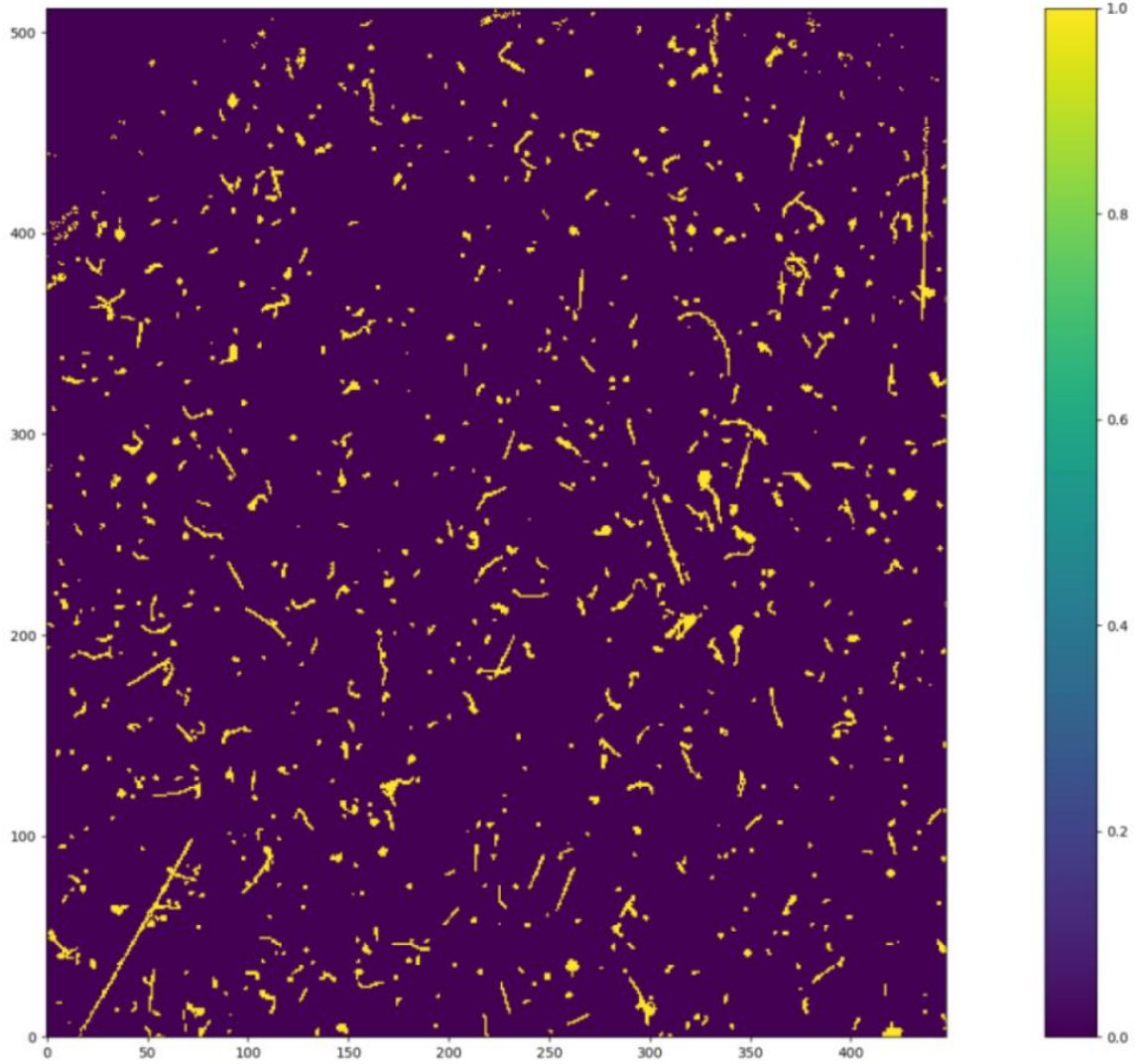
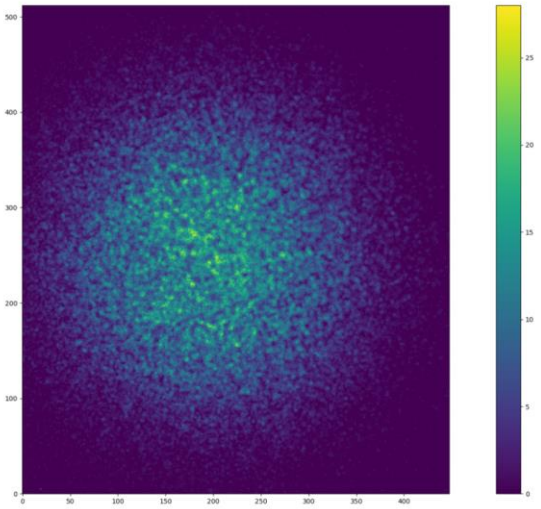
2. Cosmic Ray Test

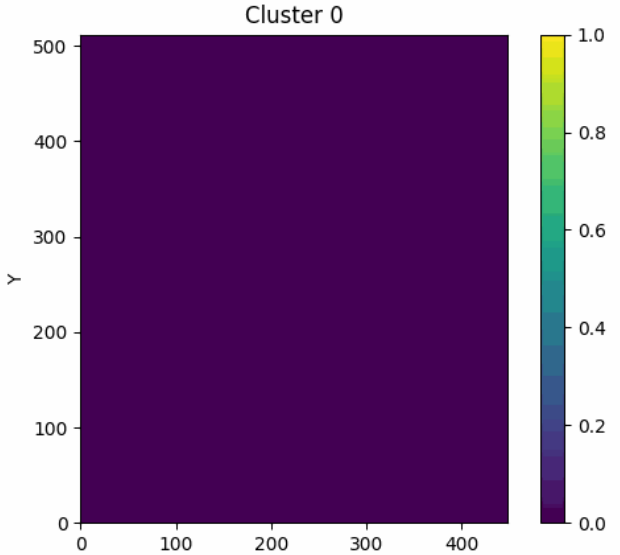


30min cosmic

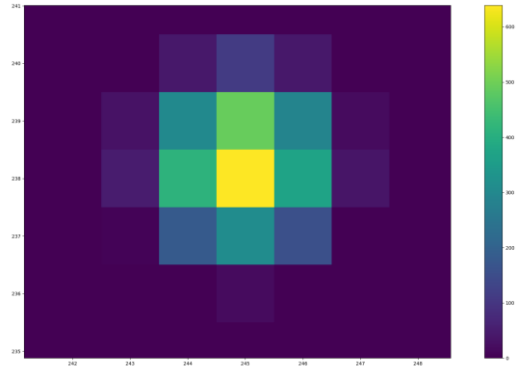
3. Am241 α Source-TOT/TOA



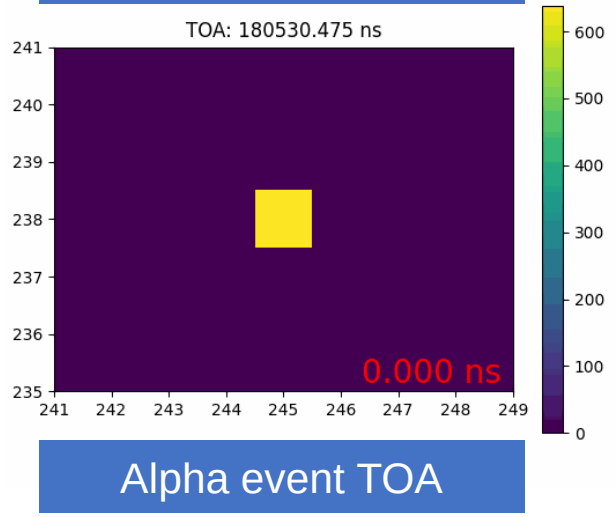
60s Am241 exposure



500 α events



Alpha event TOT



Alpha event TOA

X-ray Test #1

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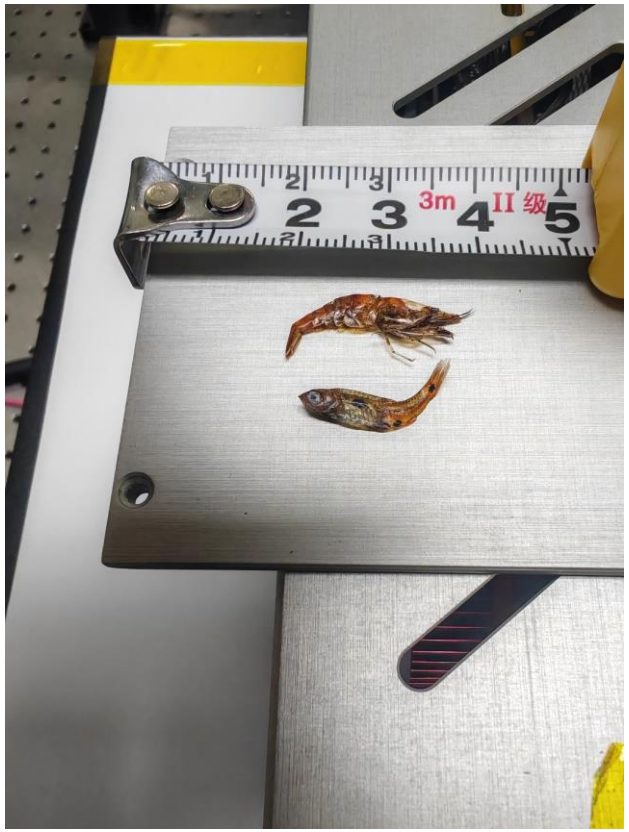
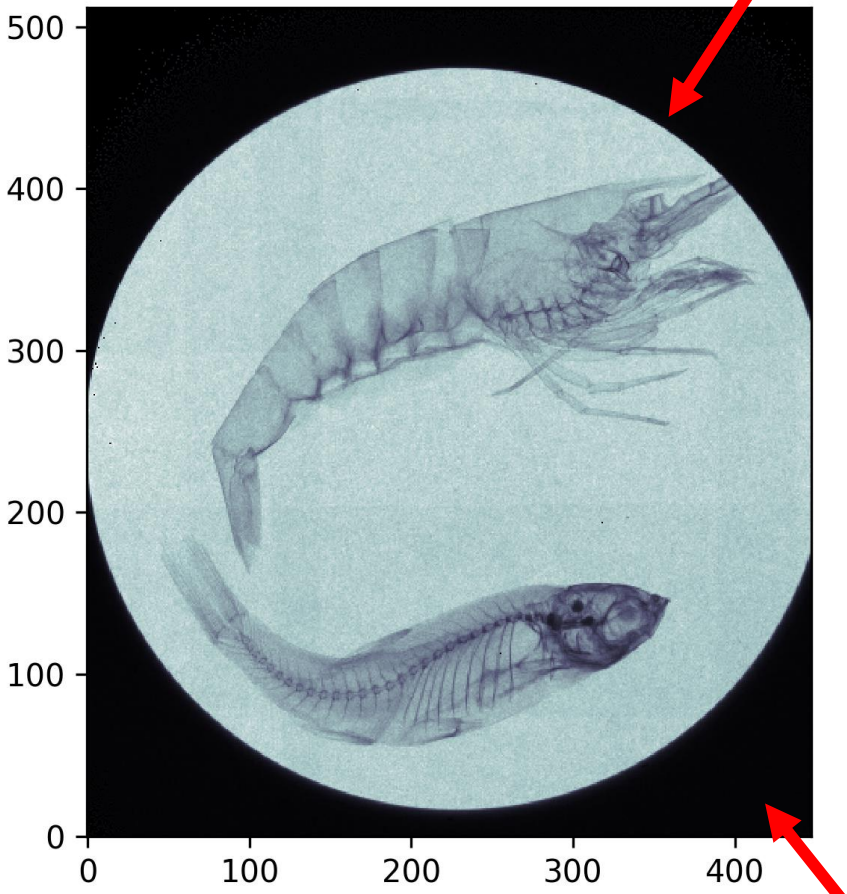
4. Timepix4 work in TOT/TOA mode

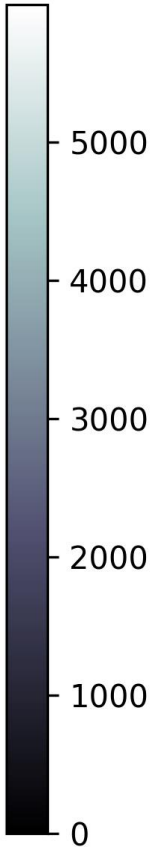
D：2.54cm

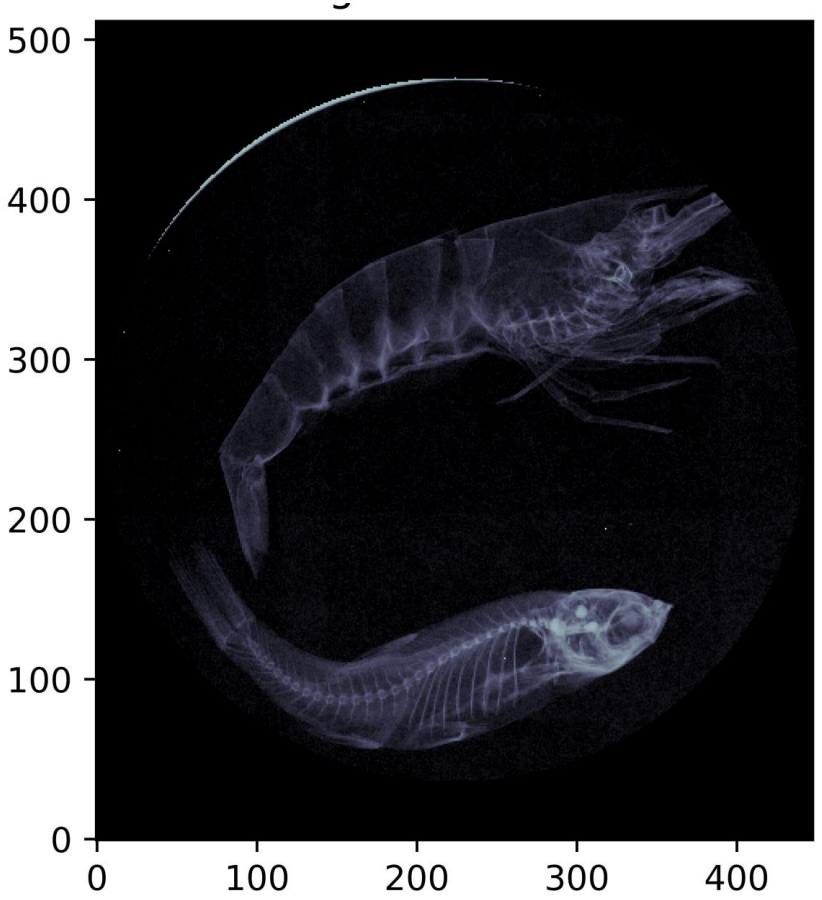


Sample



Event data reconstructed





Background removed

- Operating as expected, clear imaging results can be obtained.

Raw Data, No Flat-Field Correction

X-ray Test #2

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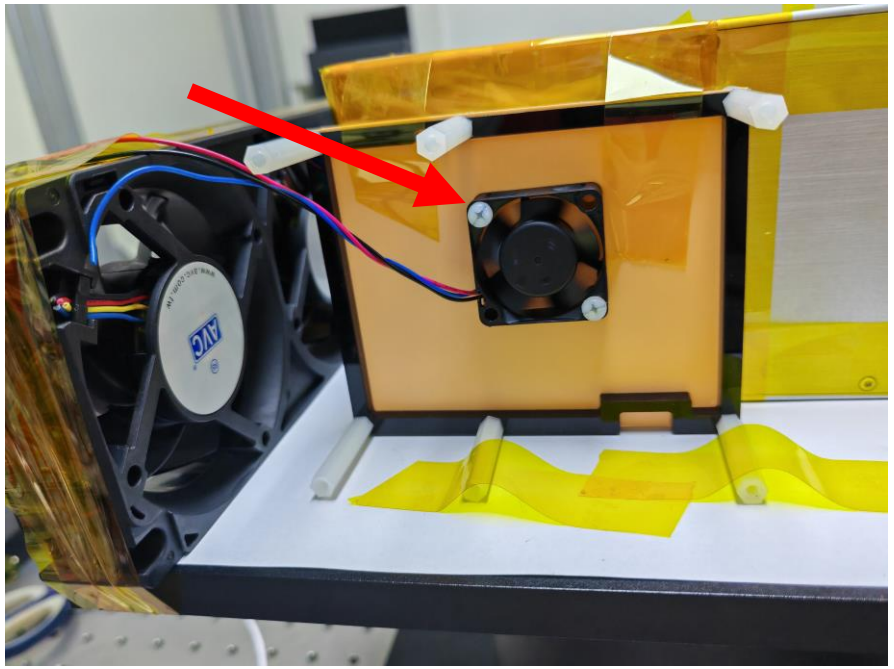
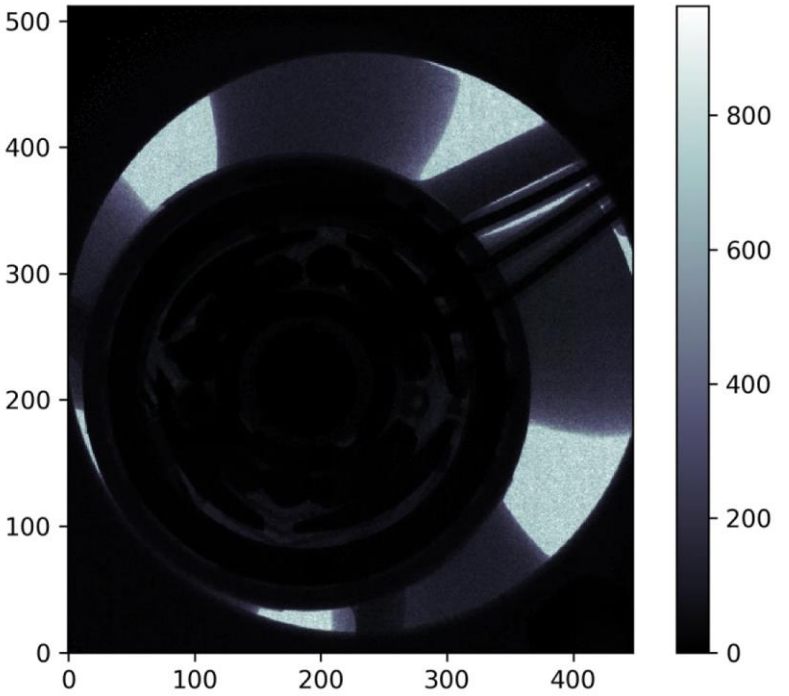
5. Timepix4 work in PC24 mode

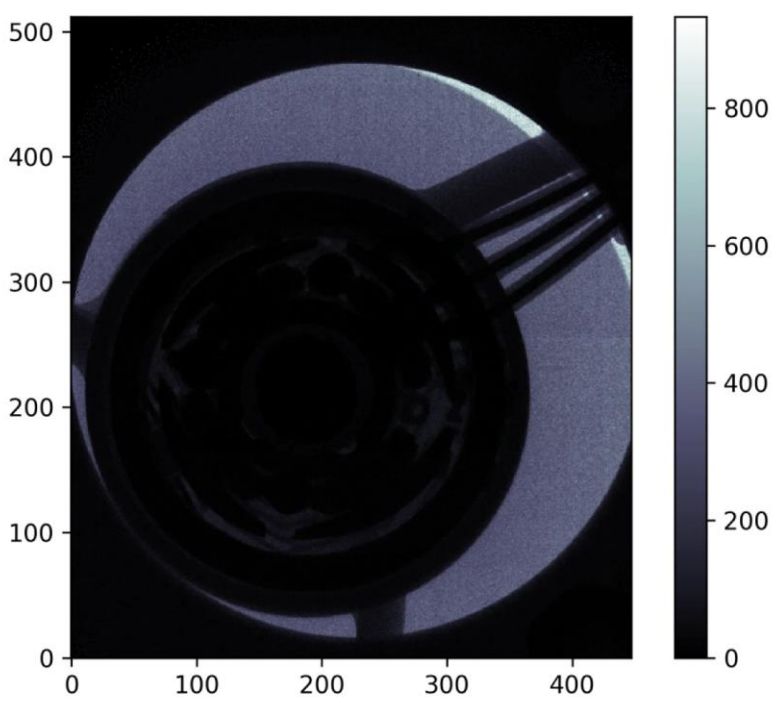
- Preliminary experiment on dynamic imaging based on event-driven mode using Timepix4.



A rotating fan sample



Fan stationary for 1 second



Fan rotating at constant speed for 1 second

X-ray Test #2

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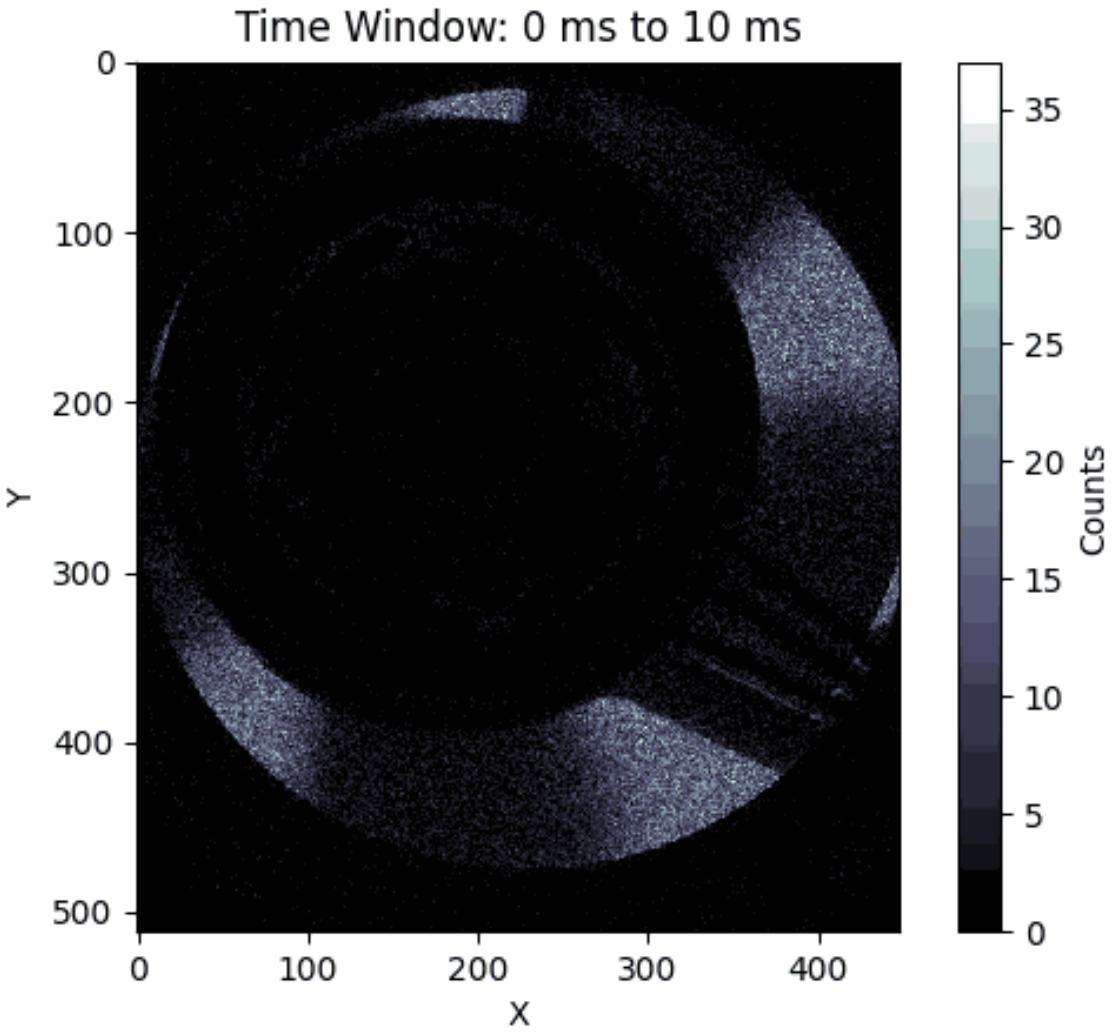
SNS

6. Dynamic reconstruction（100Hz for 1 second）



~60Mhits

Work Mode	Theoretical FPS	Bandwidth
Event 64bit	~	160Gbps（2500Mhits）
Event 64bit	~	5.12Gbps（80Mhits）
Frame @8bit	80KHz	160Gbps
Frame @8bit	40KHz	80Gbps
Frame @8bit	2.5KHz	5.12Gbps

- The current frame rate is limited by the 10G UDP network bandwidth.
- Development of a 40G UDP based on FPGA is in progress.

Contents

Summary and Plan

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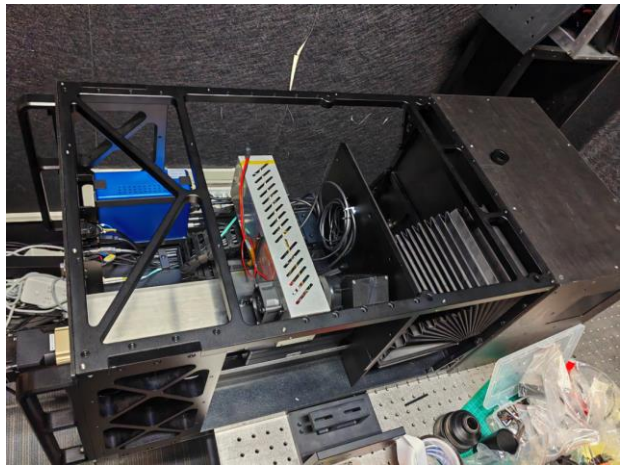
➢ Summary

- Energy-resolved neutron imaging has significant potential applications in various fields such as new materials, aerospace and industry .
- **A event-driven readout camera CTPX1 has been developed based on the advanced pixel readout chip Timepix4.**
  - Supports a maximum chip readout bandwidth of **80Gbps** and a backend readout bandwidth of **40Gbps**.
  - Tests with cosmic rays , alpha radiation sources and X-rays.
- The experimental results shows that the camera is working as expected.



➢ Next Steps

- CTPX1 has been installed on the CSNS neutron imaging detector.
- Ready for the next CSNS Run starting on October 6th.
- Developing real-time hardware algorithms for neutron imaging to reduce the amount of readout data.

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THANKS!