



# Timepix4像素探测器读出电子学研究进展及应用

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扫一扫上面的二维码图案, 加我为朋友。



中国科学院高能物理研究所  
Institute of High Energy Physics Chinese Academy of Sciences



中国科学技术大学  
University of Science and Technology of China

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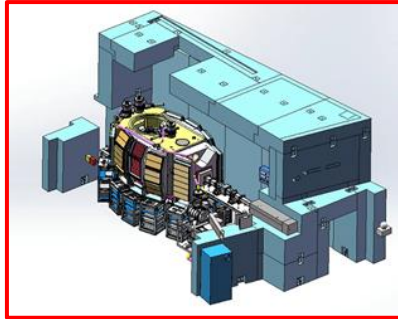
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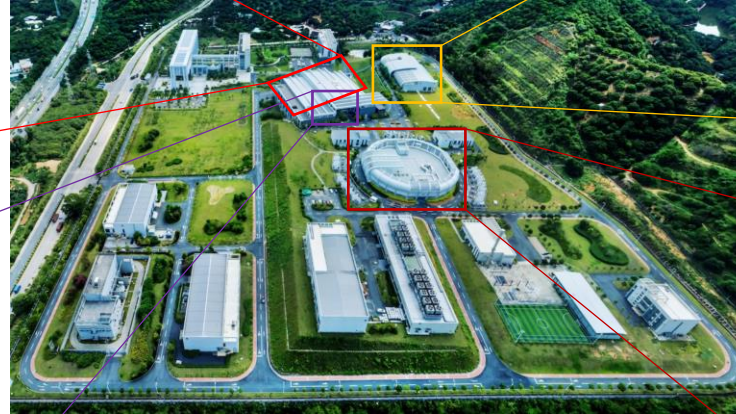
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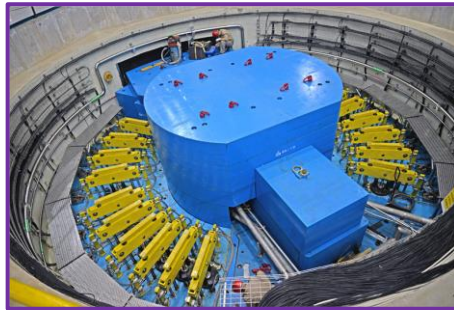




Neutron Instruments



Linear Accelerator



Target Station



Rapid Cycling Synchrotron

- CSNS is the first spallation neutron source in China, in operating since 2017
  - Pulse frequency: 25 Hz
  - Power: 120 kW (500 kW planned CSNS-II), 1.6 GeV proton + tungsten target
  - Beamlines: 20 + proton/muon test beams planned
  - Neutron Instruments: 8 in operation/commissioning, 2 being built, 7 planned
- ~ 500 staff, postdocs and students working at CSNS for operating, developing and researching

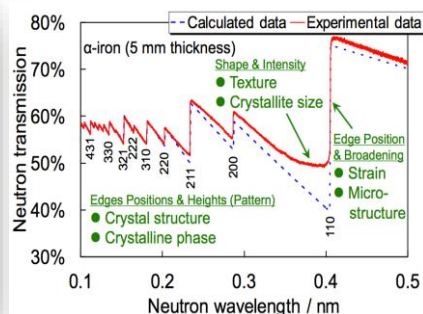
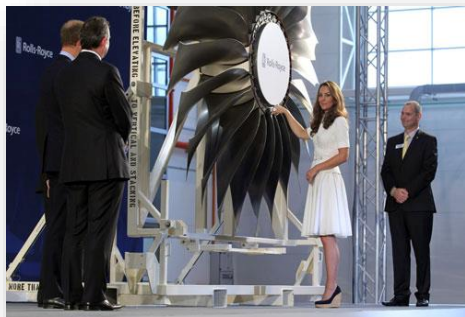
# 中子成像朝着能量分辨方向发展

## 中子的优势:

- I. 电中性, 穿透力强, 轻元素敏感, 同位素分辨, 有磁矩, 可用于磁性微观分析。
- II. 与X射线技术互补, 是研究物质微观结构的重要手段。

## 能量分辨中子成像技术在**新能源、新材料、航空航天**等领域有重大潜力

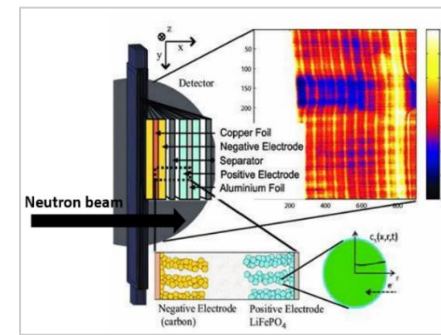
工业皇冠-航空发动机叶片



高铁车轮金属疲劳研究

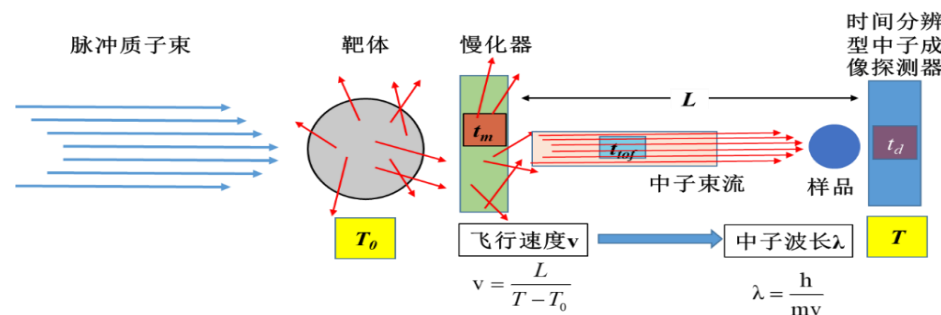
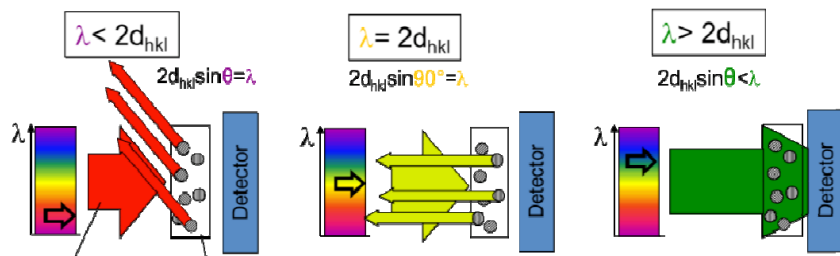


锂电池电极材料研究

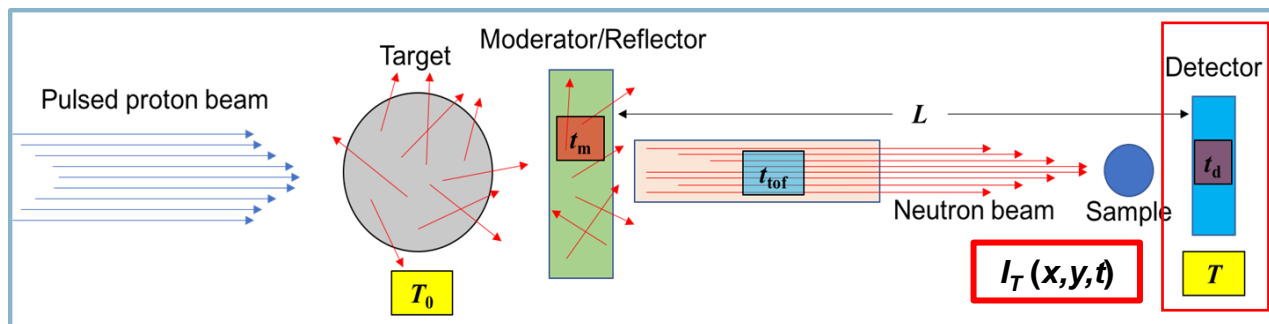


能量分辨和高空间分辨是中子成像领域未来发展的方向, 结合飞行时间方法, 关键需要研制高空间和高时间分辨的成像探测器。

布拉格衍射:  $2d\sin\theta = \lambda$

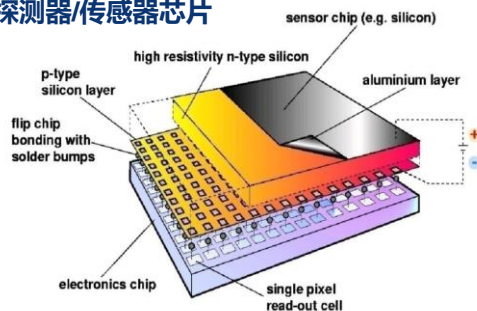


# 能量选择中子成像与像素探测器芯片

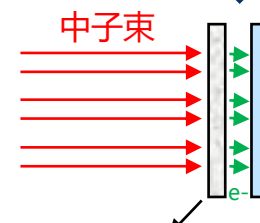
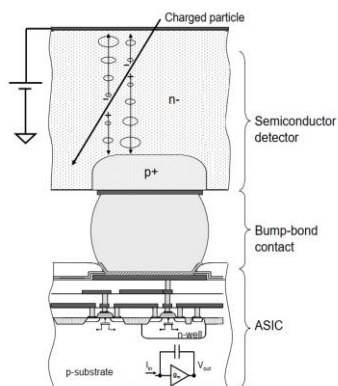


能量选择中子成像探测器结构

## 探测器/传感器芯片



像素探测器读出芯片



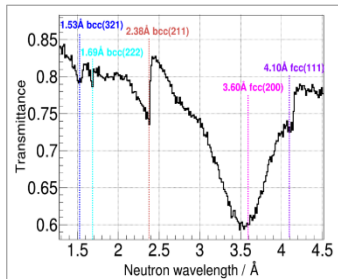
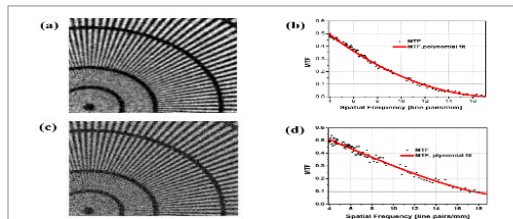
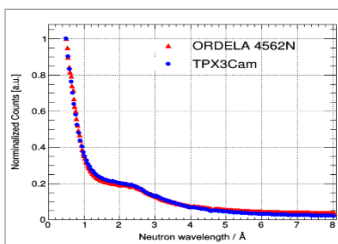
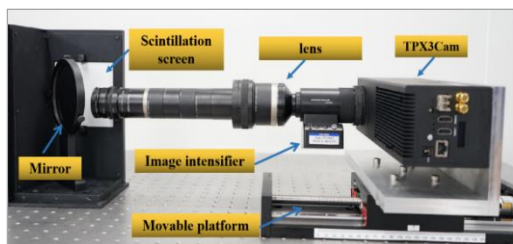
中子转换层  
- 闪烁屏+光电转换  
- 中子敏感MCP

像素读出芯片  
- 输出击中位置  
- 到达时间测量

- 高性能像素探测器读出芯片是能量选择中子成像探测器中必不可少的一部分
- 领域内最好的之一为Medipix/Timepix系列像素探测器读出芯片
- CSNS成像谱仪中子束线：20 cm x 20 cm，积分通量  $8 \times 10^{10}$  n/s



能量分辨中子成像探测器，可实现微秒级高时间分辨和微米级高空间分辨率，波长分辨约1%



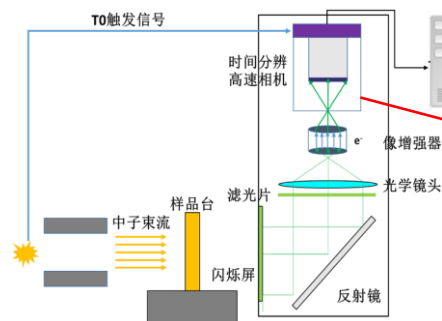
最新结果: 20  $\mu\text{m}$  (25 lp/mm)

- 该技术被国际上中子成像最顶级的两个实验室德国FRMII和瑞士PSI进行跟踪研究，其首篇文章于2021年11月发表在Scientific reports, 被形容为打破了传统中子成像技术边界
- 被美国布鲁克海文国家实验室(BNL)的成像专家Prof. Nomerotski, Andrei评价为新应用和新方法

## nMCP探测器关键技术指标及不足

主要技术指标	技术劣势
成像视野: 28mm*28mm	成像视野固定, 不能调节, 需要分子泵维持高真空
位置分辨: $\sim 20 \mu\text{m}$	空间分辨率无法突破 $10 \mu\text{m}$
时间分辨: $\sim 1 \mu\text{s}$	芯片处在中子束线上, 存在辐照损伤风险

核心部件: TPX3相机 (只集成了一片Timepix3芯片, 相机单价  $\sim \text{¥}120\text{万}$ )



能否自研此类相机? 如何获得高性能的事例型像素探测器读出芯片?

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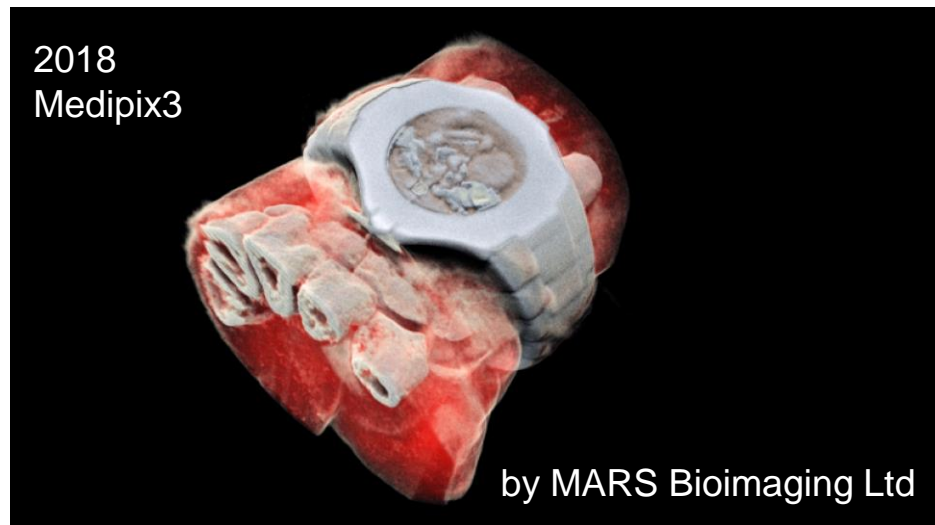
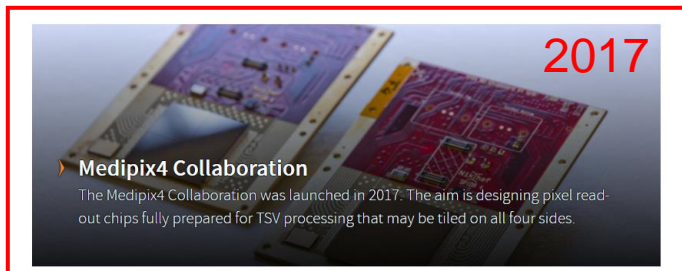
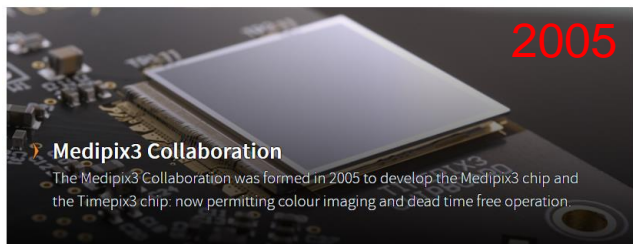
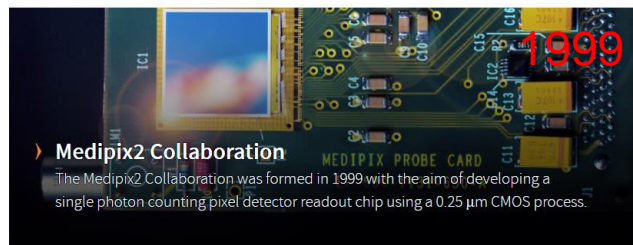
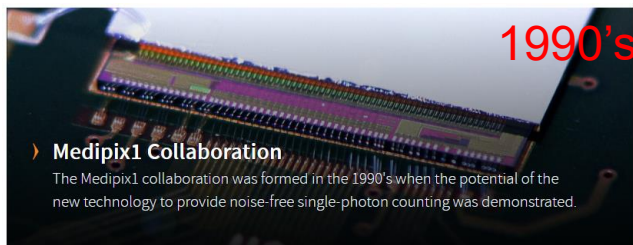
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# Medipix4合作组简介



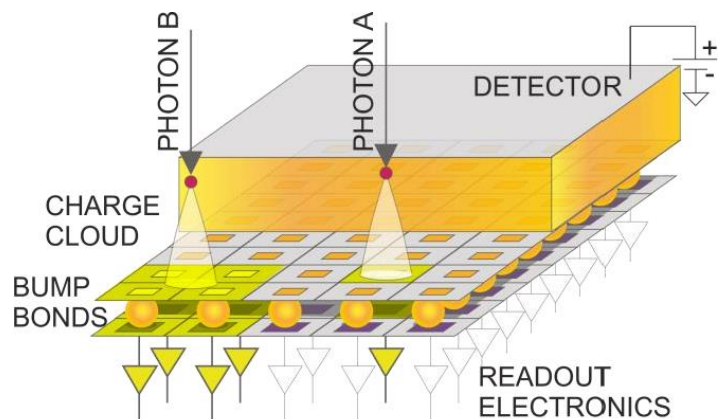
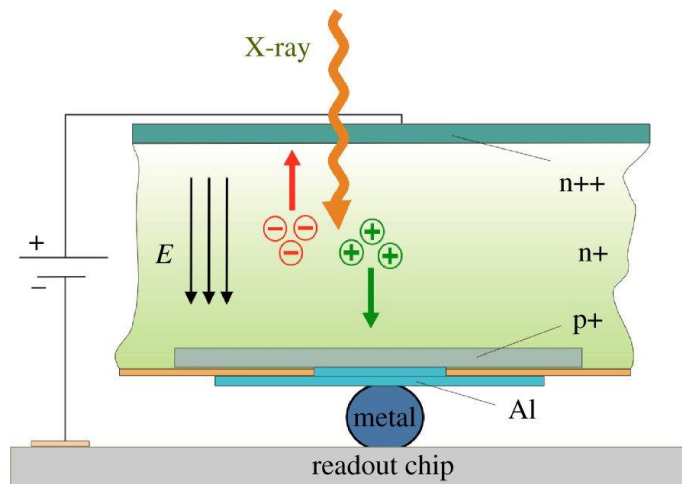
- Medipix系列合作组是由CERN领导的致力于国际先进像素探测器研发与应用的国际合作学术组织，至今已有20多年历史，研发了4代 像素探测器读出芯片



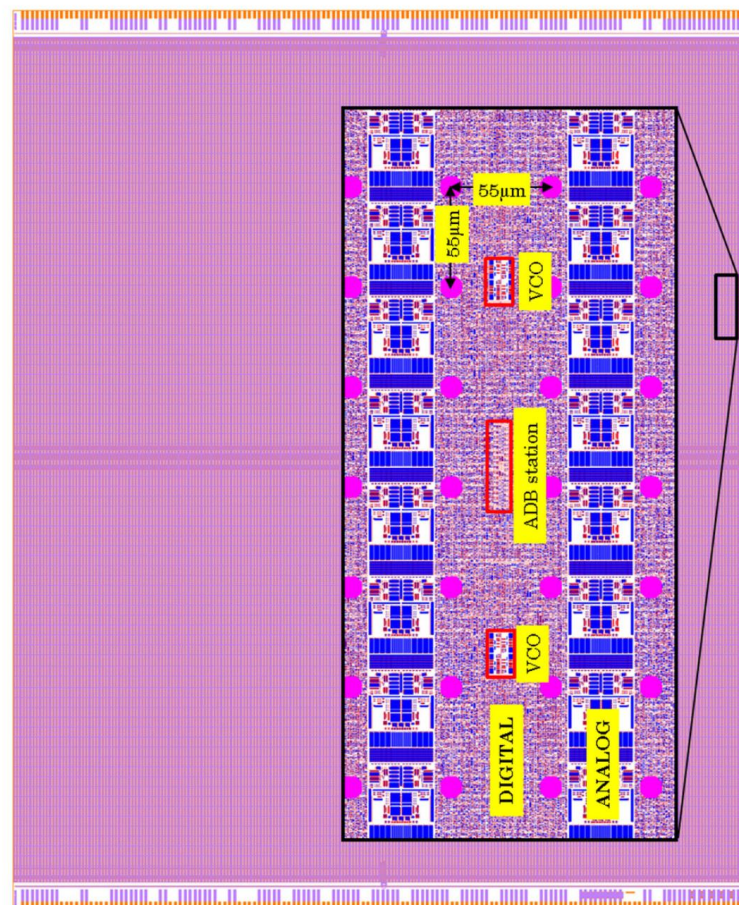
- 针对每代像素探测器的读出芯片研发与应用，成立相应的代际合作组
  - 每个代际合作组专注于两款像素探测器读出芯片研发：Medipix（帧驱动）/Timepix（事例驱动）
  - 最新的代际合作组：Medipix4，成立于2017年，目前已完成Timepix4（2019）/Medipix4（2023）两款芯片的设计和流片
- Medipix4合作组现有20个成员单位：
  - 科研机构：CERN、法国CEA、荷兰Nikhef 等
  - 大学：牛津大学，加州大学伯克利分校 等
  - 大装置：ESRF、钻石光源 等
  - IHEP-CSNS于2022年底正式加入Medipix4合作组，开始基于Timepix4的高速辐射探测器（相机）



# Timepix4: 混合式像素探测器读出芯片



Single hit (electrical signal) pixel-level processor



Features of the Timepix4 chip

technology	TSMC 65nm - 10 metal		
pixel size	55 x 55 µm		
chip arrangement	4-side buttable 3x "hidden" periphery TSV I/O pixel matrix: 512 x 448		
sensitive area	6.94 cm <sup>2</sup>		
interface	3x 147 I/O TSV / Wirebond		
Readout Modes	Tracking (data driven)	mode	<b>ToT &amp; ToA</b>
		data	64-bit per hit
	Imaging (frame-based)	max hit rate	3.58x10 <sup>6</sup> hits/mm <sup>2</sup> /s (10.8 KHz / pixel)
		Mode	<b>CRW: Pixel Counter (8 /16-bit)</b>
Imaging (frame-based)	frame rate	up to 89kFPS	
	max hit rate	~ 5 x 10 <sup>9</sup> hits/mm <sup>2</sup> /s	
Energy resolution @ Si sensor	~ 1keV FWHM		
ENC @ Cin = 75fF	80e <sup>-</sup> rms		
minimum threshold	~ 500 e <sup>-</sup>		
hit arrival timing (ToA)	<b>LSB=195ps</b> , range: 1.638ms		
charge measurement (ToT)	accuracy: 80e <sup>-</sup> rms, range:200ke <sup>-</sup>		
data readout bandwidth	≤163.84 Gbps (16x @ <b>10.24 Gbps</b> )		
Power Supply Voltage	1.2V		
Power	~3.5W		

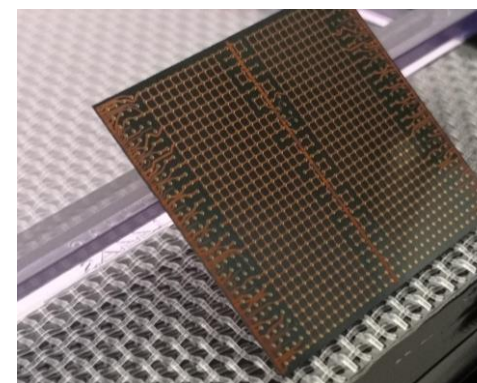
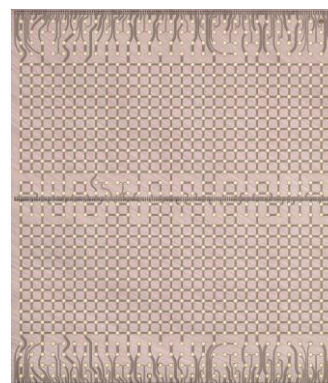
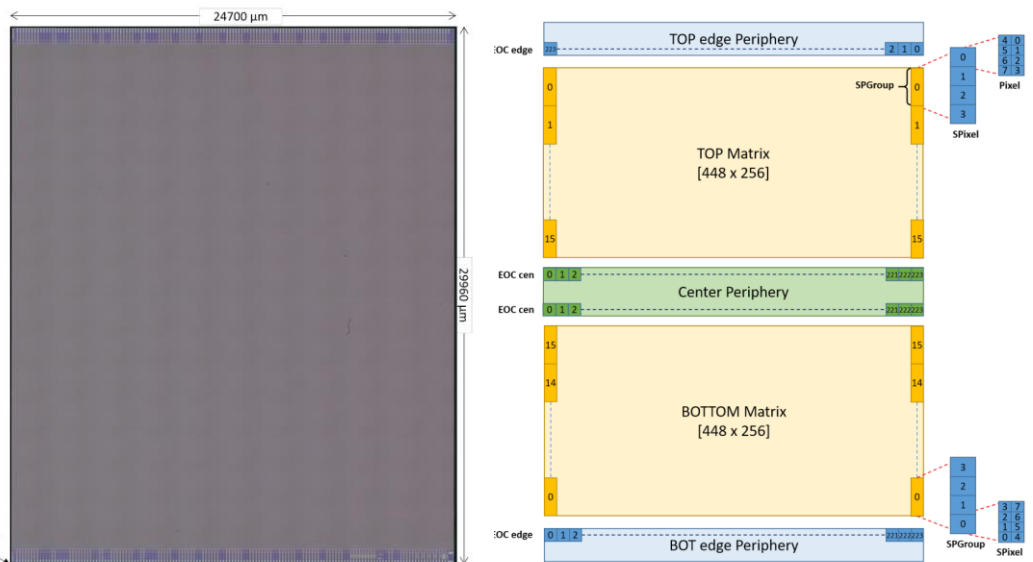
- 四面可拼接，具有同时进行位置、时间和能量测量的能力，适用于高速辐射成像领域

# Timepix4: 一种混合式像素探测器读出芯片

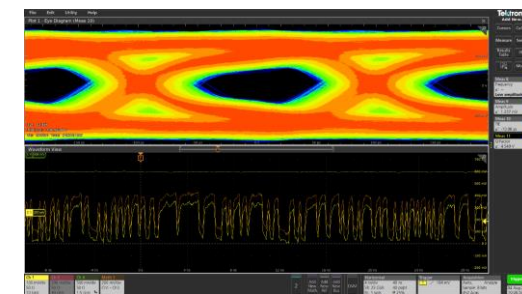
		Timepix3 (2013)	Timepix4 (2019/20)		
Technology		IBM 130 nm – 8 metal	TSMC 65 nm – 10 metal		
Pixel size		55 x 55 $\mu\text{m}$	55 x 55 $\mu\text{m}$		
Pixel arrangement		3-side buttable 256 x 256	4-side buttable (TSV) 512 x 448	3.5 x	
Sensitive area		1.98 $\text{cm}^2$	6.94 $\text{cm}^2$		
Readout modes	Data driven (tracking)	Mode	ToT and TOA		
		Event packet	48-bit	64-bit	
		Max rate	< 43 Mhits/ $\text{cm}^2/\text{s}$	357.6 Mhits/ $\text{cm}^2/\text{s}$	8 x
	Frame Based (imaging)	Pix rate equiv.	1.3 kHz/pix average	10.8 kHz/pix average	
		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/ $\text{cm}^2/\text{s}$	~ 800 Ghits/ $\text{cm}^2/\text{s}$	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		$\leq 5.12$ Gbps (8 x 640 Mbps)	$\leq 163.8$ Gbps (16 x 10.2 Gbps)	32 x	
Target minimum threshold		< 500 $e^-$	< 500 $e^-$		

## 关键参数

- 输入信号: 电信号, 最低阈值500电子
- 像素尺寸: 55 x 55  $\mu\text{m}$
- 像素数量: 512 x 448 (23万像素)
- 探测面积: 6.94  $\text{cm}^2$
- 读出信息: 位置、到达时间(TOA)、能量 (TOT)
- 时间分辨: ~ 200 ps
- 最高计数率: 357 MHz/ $\text{cm}^2/\text{s}$ , 2.47GHz/芯片
- 帧读出模式: 最高89kfps@8-bit深度
- 数据读出: 16 x 10 Gbps SERDES / 芯片
- 功耗: 与计数率相关, 最高约6瓦 (~1W/ $\text{cm}^2$ )
- 连接sensor: 倒装焊
- 连接PCB: WB (两边), TSV (两边+中间)



Timepix4 with TSV



5G PRBS through TSV

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读出电子学研制及测试进展

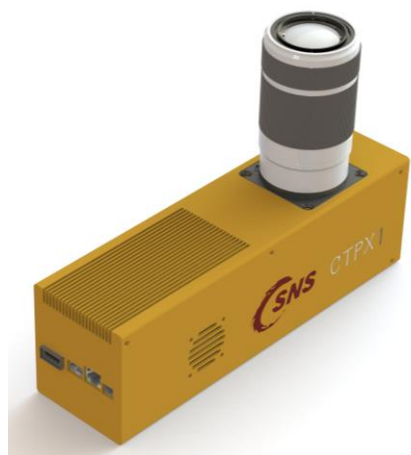
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大面积阵列读出电子学规划

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总结





## 单模块探测器CTPX1

- 核心硬件基本完成
- 参数调试/机器研究中
- 计划6-7月进行中子实验
- X射线实验、电镜实验

## 4模块探测器CTPX4 (2024H2)

- 2.8 cm x 9.8 cm 探测面积
- 读出电子学正在进行设计
- 预计8月完成制作
- 计划年底前完成中子实验

## 大面积阵列 (2025 – 2026)

- 20 cm x 20 cm 探测面积
- 海量数据读出 (8.96Tbps)
- 严峻的散热问题
- 多模块同步
- 成像谱仪, 单晶谱仪\*

进口相机替代, 验证实验

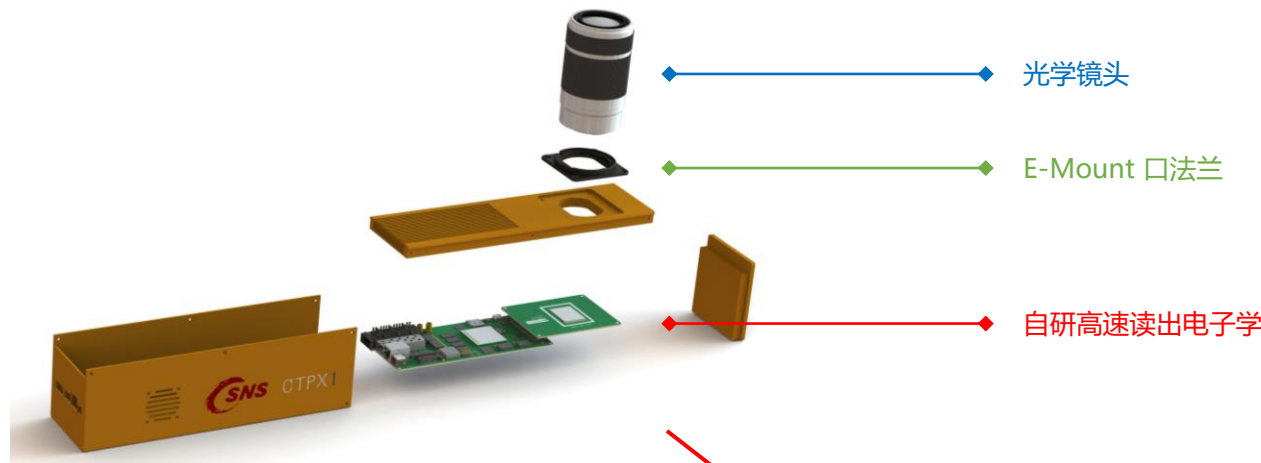
更大探测面积, 中等规模实验

最终形态, 推广应用

# 自研高速事例型像素探测器 - CTPX1



CTPX1工程样机效果图



CTPX1工程样机结构图

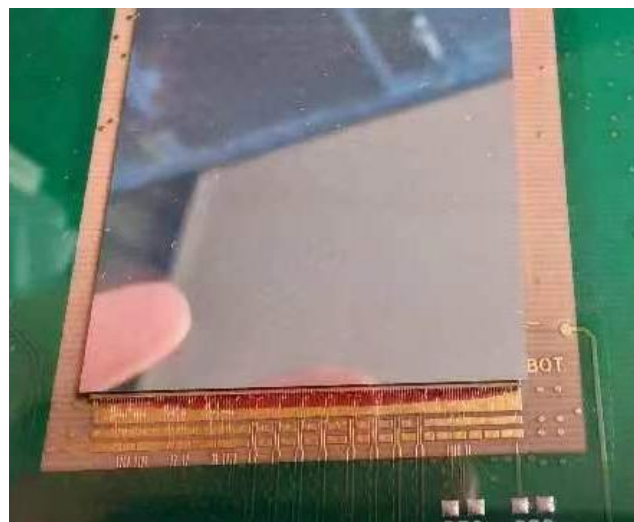
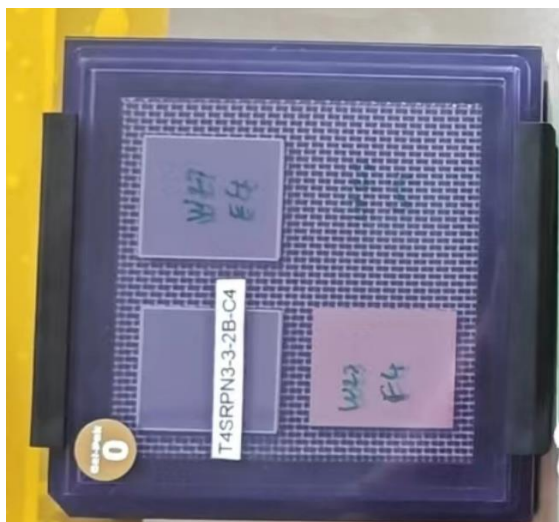
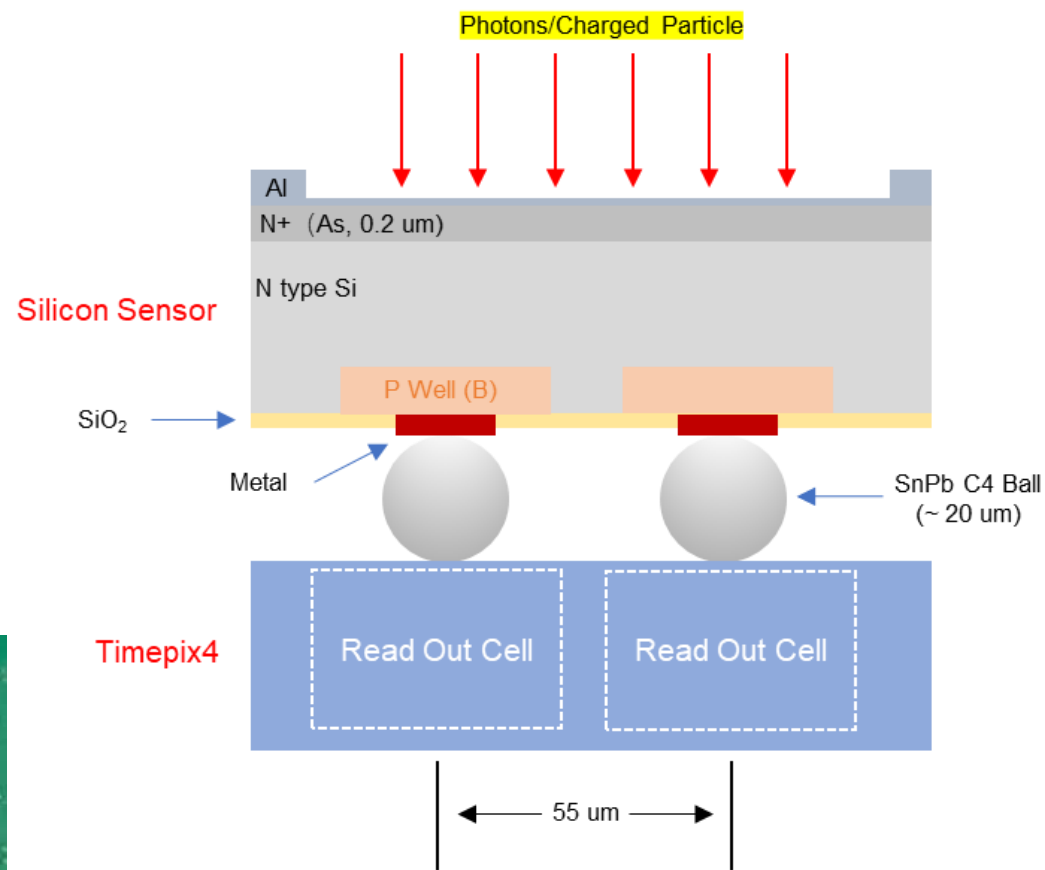
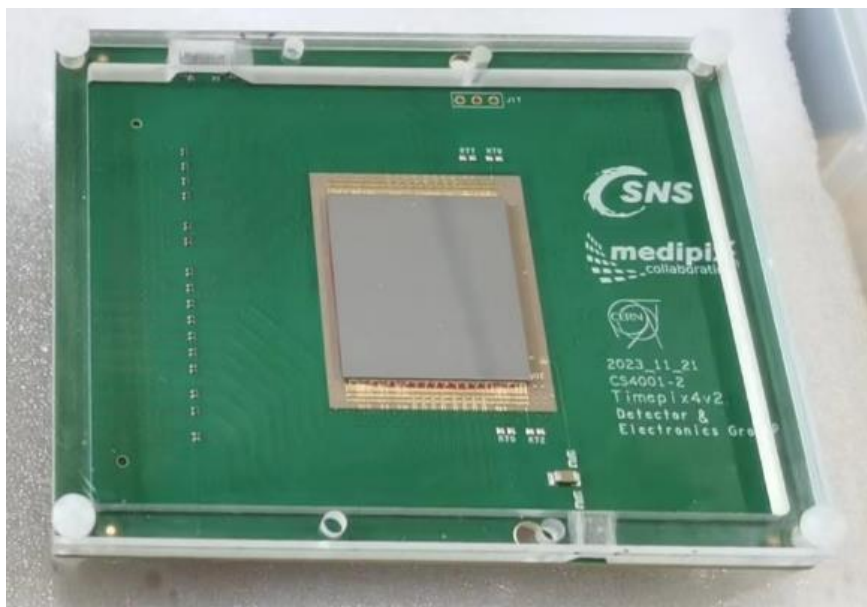


主要参数	ASI TPX3Cam	CSNS CTPX1	备注
灵敏面积	1.4 cm x 1.4 cm	2.8 cm x 2.5 cm	× 2.57
像素阵列	256 x 256	512 x 448	× 2.57
像素单元	55 um	55 um	相同
时间分辨	1.6 ns	200 ps	× 5
读出带宽	10GbE	40 GbE	× 4
数据缓存	DDR3	DDR4	无损缓存
最高计数率	80 MHz	> 1GHz	



- 主要参数预计将比现在使用的进口相机有较大提升，并且可以进行二次开发

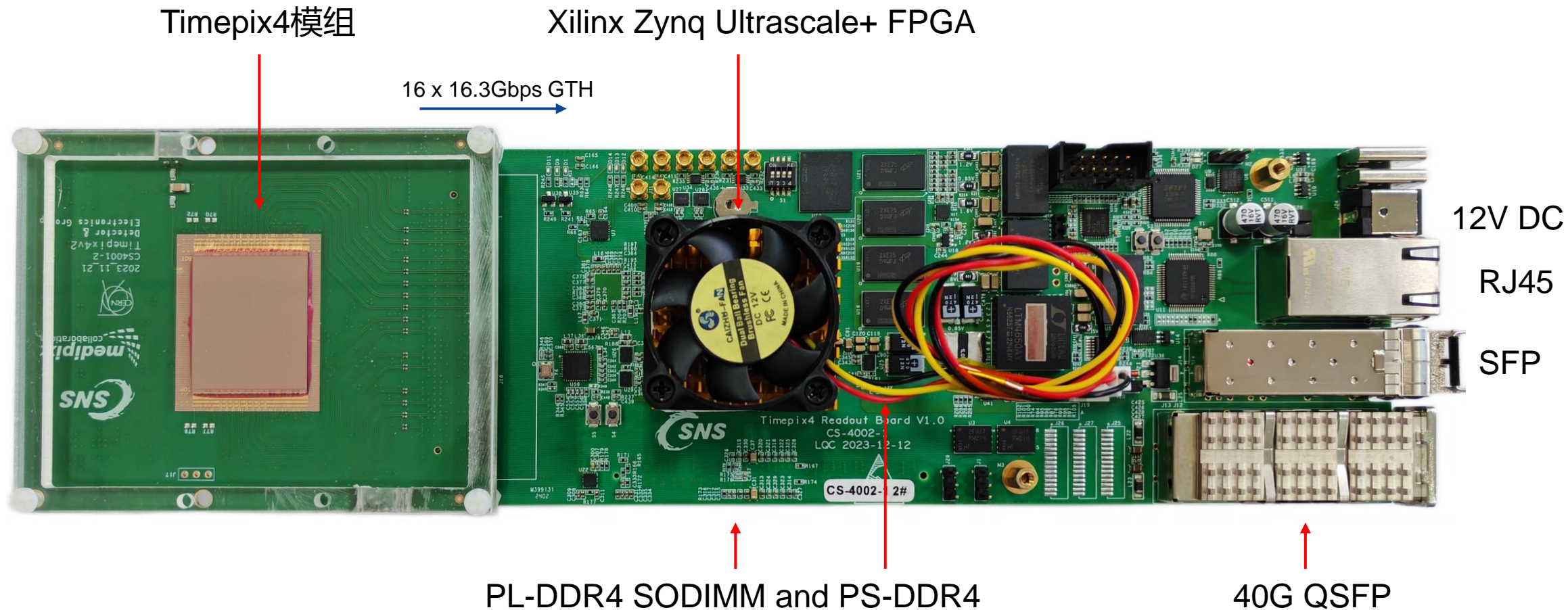
# CTPX1 – 硅传感器模组



- 300/500 um SI – PIN (包含开窗模块)
- 由Advacam公司制作和组装模块

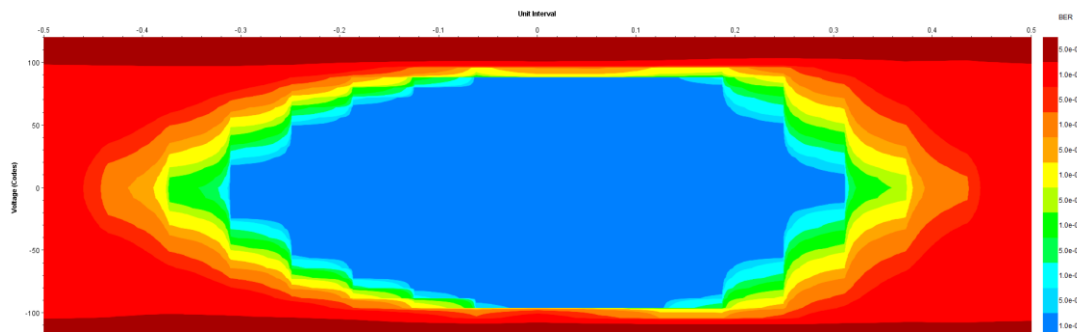


# CTPX1 – 自研高速读出电子学



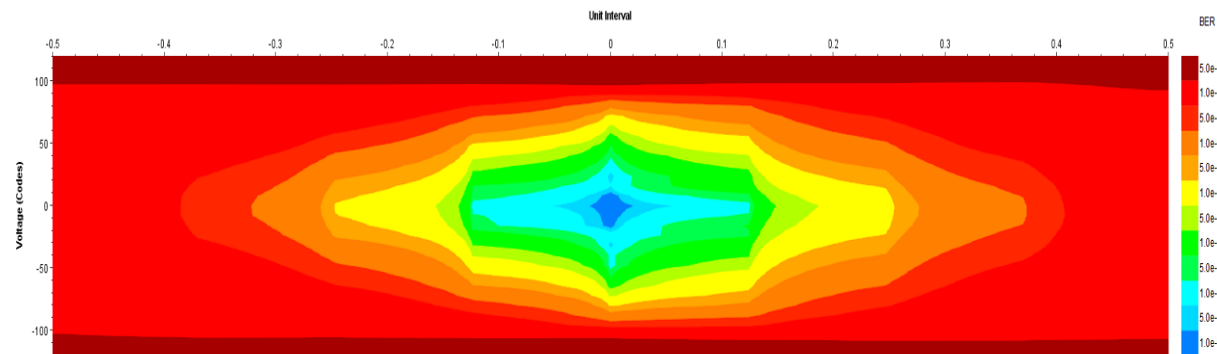
# CTPX1 – 高速读出电子学链路测试

- 1.28/2.56 Gbps: No errors , BER <  $10^{-14}$



Summary		Metrics		Settings	
Name:	SCAN_1	Link area:	1088	Link settings:	N/A
Description:	Scan 1	Open UI %:	58.82	Horizontal increment:	8
Started:	2024-Mar-03 05:36:33	Horizontal range:	-0.500 UI to 0.500 UI	Vertical increment:	8
Ended:	2024-Mar-03 05:36:35	Vertical range:	100%		

5.12 Gbps : BER <  $10^{-14}$



Summary		Metrics		Settings	
Name:	SCAN_5	Open area:	64	Link settings:	N/A
Description:	Scan 5	Open UI %:	11.11	Horizontal increment:	8
Started:	2024-Mar-03 10:26:07	Horizontal range:	-0.500 UI to 0.500 UI	Vertical increment:	8
Ended:	2024-Mar-03 10:26:08	Vertical range:	100%		

10.24 Gbps: BER:  $10^{-5} \sim 10^{-7}$

Name	Rx	Tx	Status	Bits	Errors	BER	BER Reset	Tx Pattern	Rx Pattern	Tx Pre-Cursor	Tx Post-Cursor	Tx Diff Swing	DPE Enabled	Injct Error	Tx Reset	Rx Reset	Rx PLL Status	Tx PLL Status	Loopback Mode	Rx Polat.
Link Group 0 (16)																				
Link 0	MGT_0P08TX	MGT_0P08RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 1	MGT_0P16TX	MGT_0P16RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 2	MGT_0P24TX	MGT_0P24RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 3	MGT_0P32TX	MGT_0P32RX	5.120 Gbps	2.478E13	108E2	4.396E-11	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 4	MGT_0P40TX	MGT_0P40RX	5.120 Gbps	2.598E13	0E0	4.044E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 5	MGT_0P48TX	MGT_0P48RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 6	MGT_0P56TX	MGT_0P56RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 7	MGT_0P64TX	MGT_0P64RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 8	MGT_0P72TX	MGT_0P72RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 9	MGT_0P80TX	MGT_0P80RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 10	MGT_0P88TX	MGT_0P88RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 11	MGT_0P96TX	MGT_0P96RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 12	MGT_1P04TX	MGT_1P04RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 13	MGT_1P12TX	MGT_1P12RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 14	MGT_1P20TX	MGT_1P20RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 15	MGT_1P28TX	MGT_1P28RX	5.120 Gbps	2.598E13	0E0	3.985E-14	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	

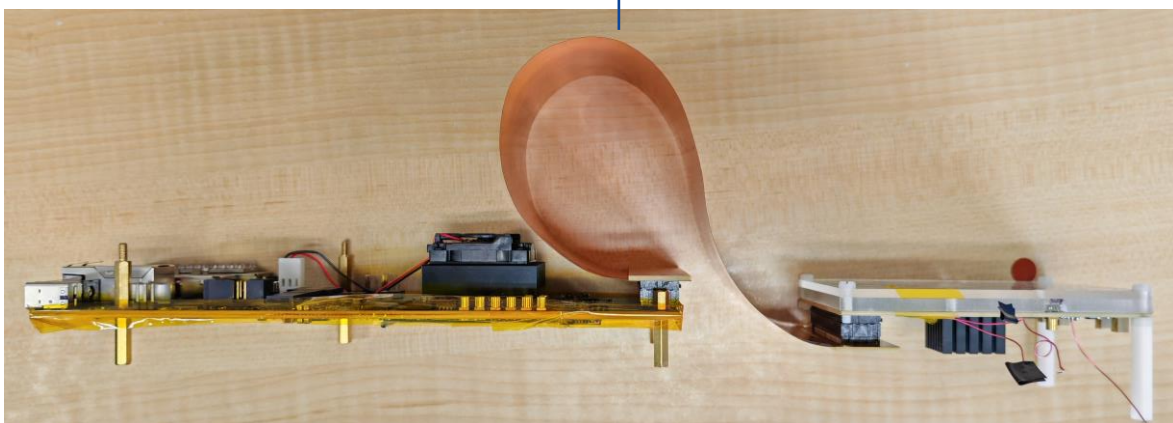
Name	Rx	Tx	Status	Bits	Errors	BER	BER Reset	Tx Pattern	Rx Pattern	Tx Pre-Cursor	Tx Post-Cursor	Tx Diff Swing	DPE Enabled	Injct Error	Tx Reset	Rx Reset	Rx PLL Status	Tx PLL Status	Loopback Mode	Rx Polat.
Link Group 0 (16)																				
Link 0	MGT_0P08TX	MGT_0P08RX	10.240 Gbps	1.039E11	8.097E4	8.750E-7	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 1	MGT_0P16TX	MGT_0P16RX	10.240 Gbps	1.039E11	4.589E4	4.417E-7	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 2	MGT_0P24TX	MGT_0P24RX	10.240 Gbps	1.042E11	1.752E5	1.686E-6	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 3	MGT_0P32TX	MGT_0P32RX	10.240 Gbps	1.042E11	2.503E5	2.408E-6	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 4	MGT_0P40TX	MGT_0P40RX	10.240 Gbps	1.042E11	2.487E5	2.373E-6	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 5	MGT_0P48TX	MGT_0P48RX	10.240 Gbps	1.042E11	1.483E5	1.348E-6	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 6	MGT_0P56TX	MGT_0P56RX	10.240 Gbps	1.042E11	9.697E4	9.229E-7	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 7	MGT_0P64TX	MGT_0P64RX	10.240 Gbps	1.042E11	1.681E4	1.605E-7	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 8	MGT_0P72TX	MGT_0P72RX	10.240 Gbps	1.042E11	1.689E4	1.739E-7	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 9	MGT_0P80TX	MGT_0P80RX	10.240 Gbps	1.042E11	8.448E4	8.12E-7	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 10	MGT_0P88TX	MGT_0P88RX	10.240 Gbps	1.039E11	7.397E3	7.119E-8	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 11	MGT_0P96TX	MGT_0P96RX	10.240 Gbps	1.039E11	1.853E5	1.88E-6	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 12	MGT_1P04TX	MGT_1P04RX	10.240 Gbps	1.039E11	1.863E4	3.225E-7	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 13	MGT_1P12TX	MGT_1P12RX	10.240 Gbps	1.039E11	3.257E4	3.133E-7	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 14	MGT_1P20TX	MGT_1P20RX	10.240 Gbps	1.039E11	9.234E3	8.883E-8	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	
Link 15	MGT_1P28TX	MGT_1P28RX	10.240 Gbps	1.042E11	1.008E4	9.882E-8	Reset	PRBS 31-04	PRBS 31-04	0.00 dB (00000)	0.00 dB (00000)	873 mV (11000)		Injct	Reset	Reset	Locked	Locked	None	

- 单芯片80Gbps稳定读出, 理论上能够支持最高计数率的50% (1.2Gcps , 45 kfps @ 8bit)
- 10.24 Gbps链路将会继续使用TSV模组进行验证

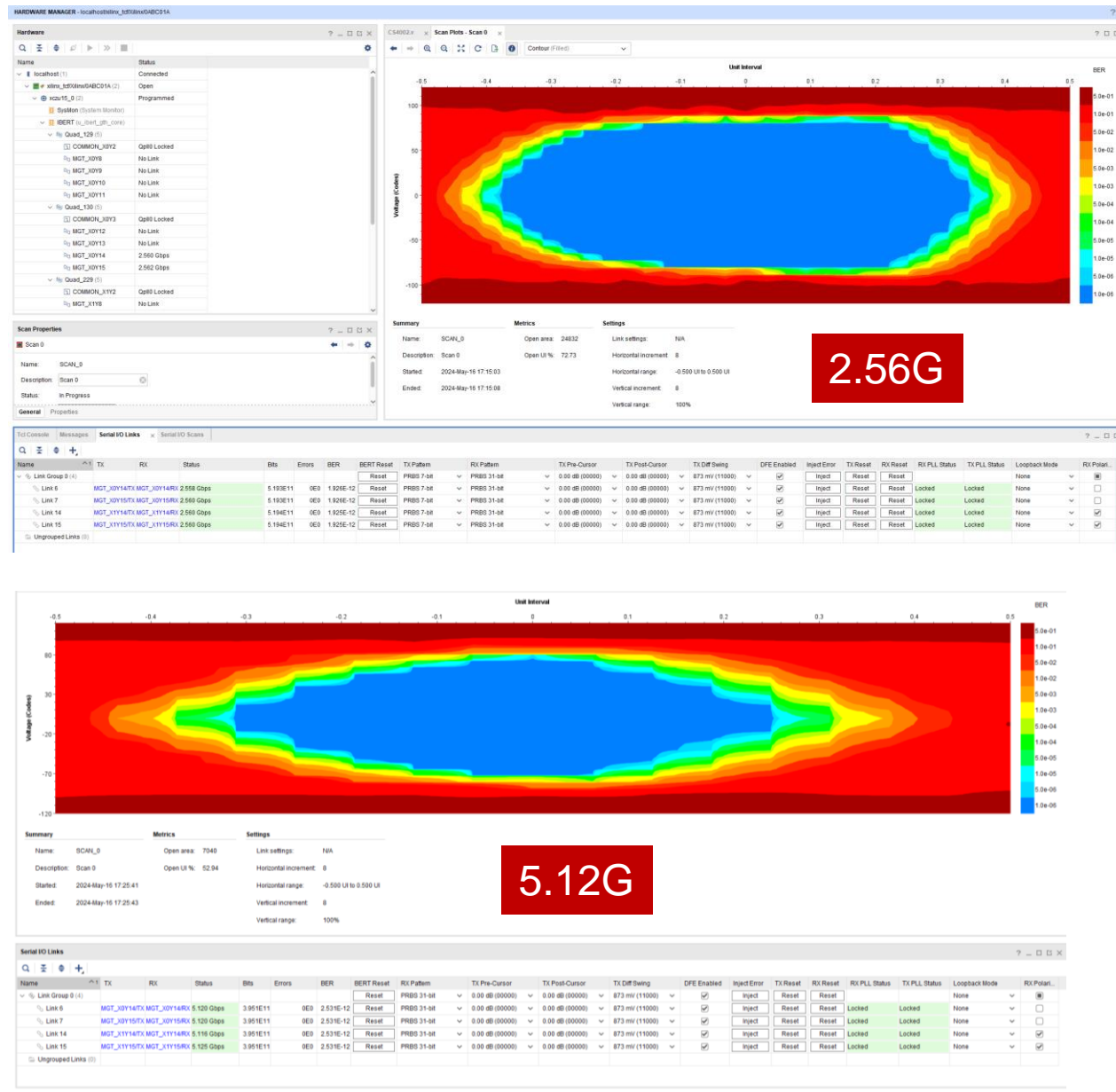


# CTPX1 – 高速读出电子学链路测试

30cm, 2层, 柔性PCB, 无阻抗匹配, 4 x GTH



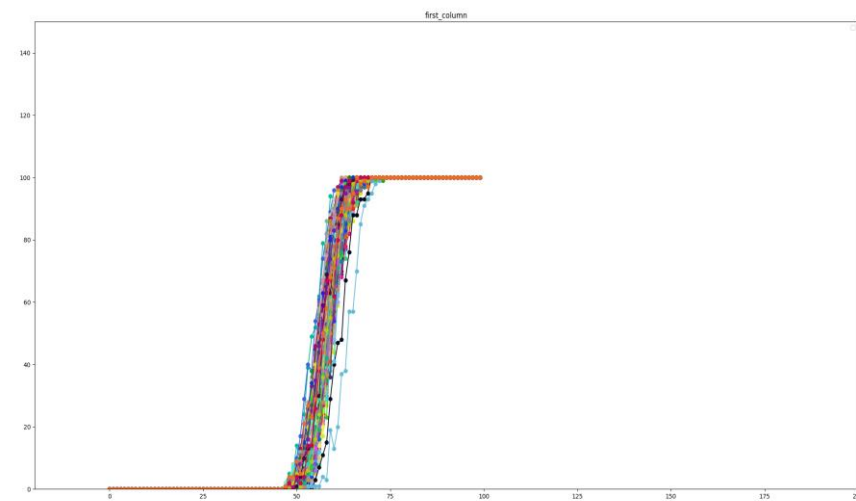
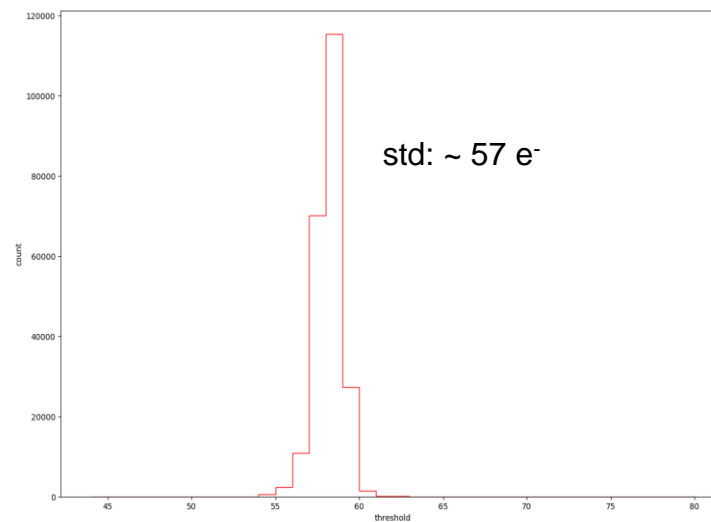
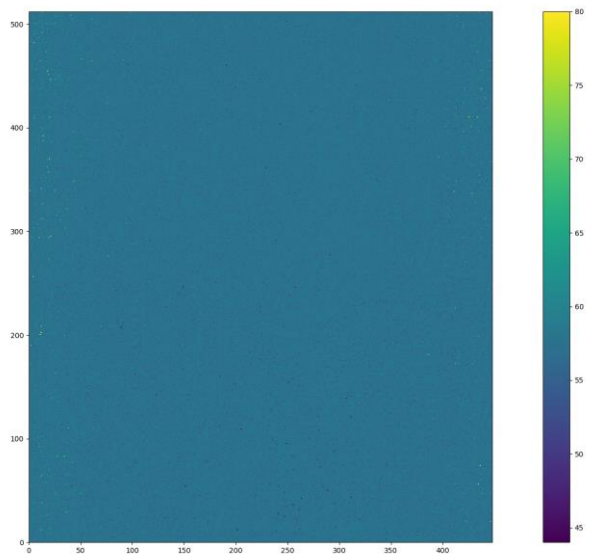
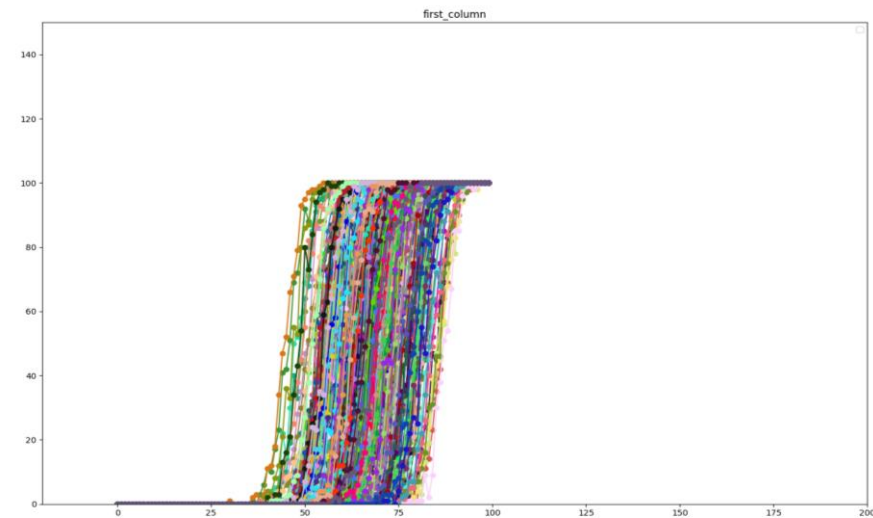
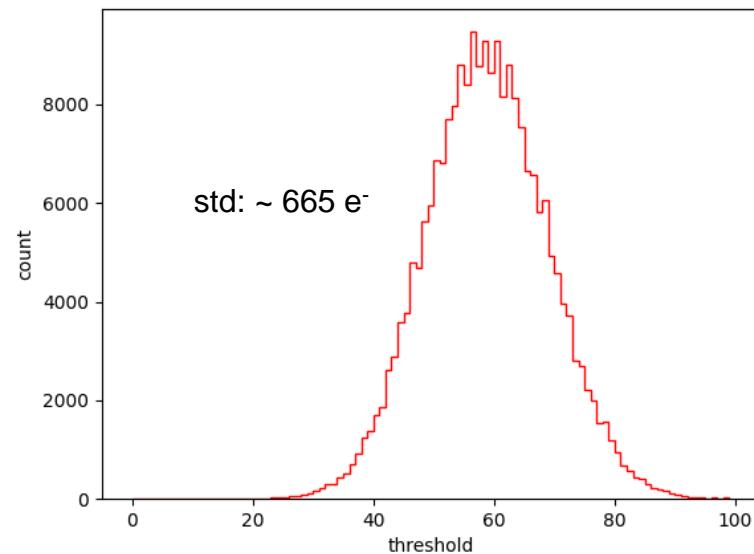
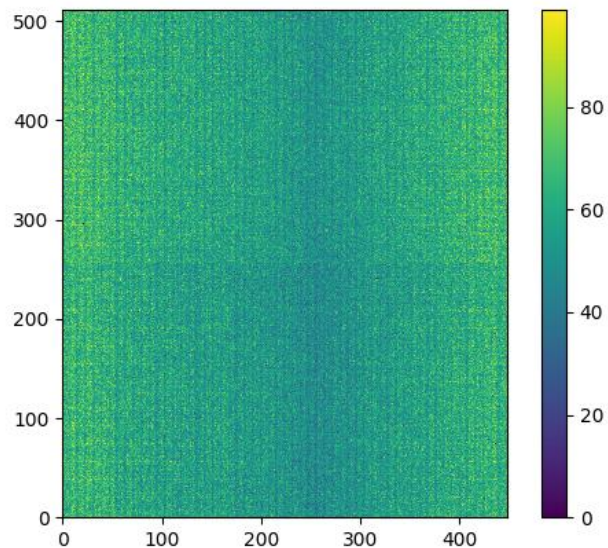
- 通过Flex PCB连接能够工作于5.12 Gbps
- 可以用于真空环境实验





# CTPX1 – 像素探测器阈值调节

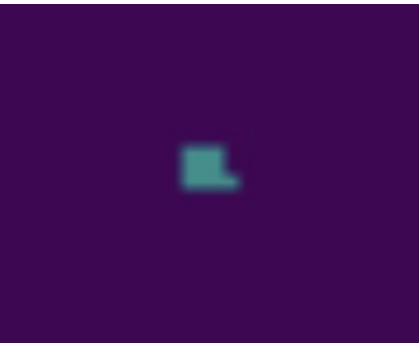
## 23万通道阈值调节



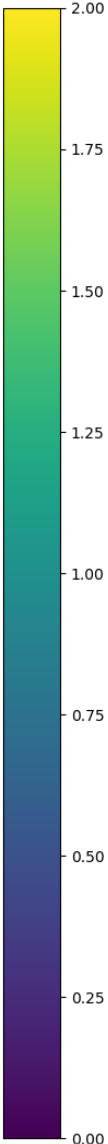
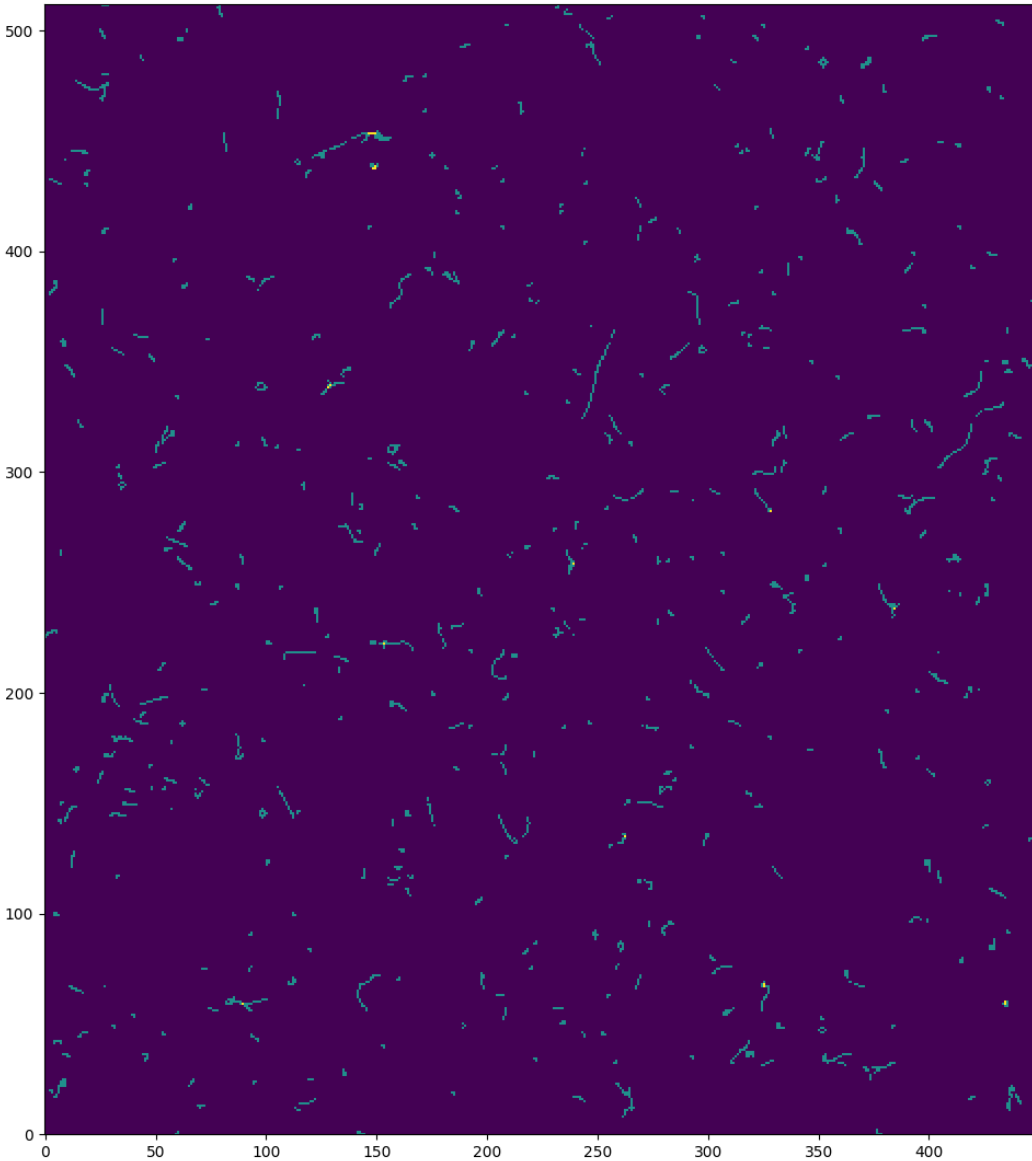
# CTPX1 – 联调测试初步结果 – 20分钟宇宙线



$\alpha$



$\gamma$

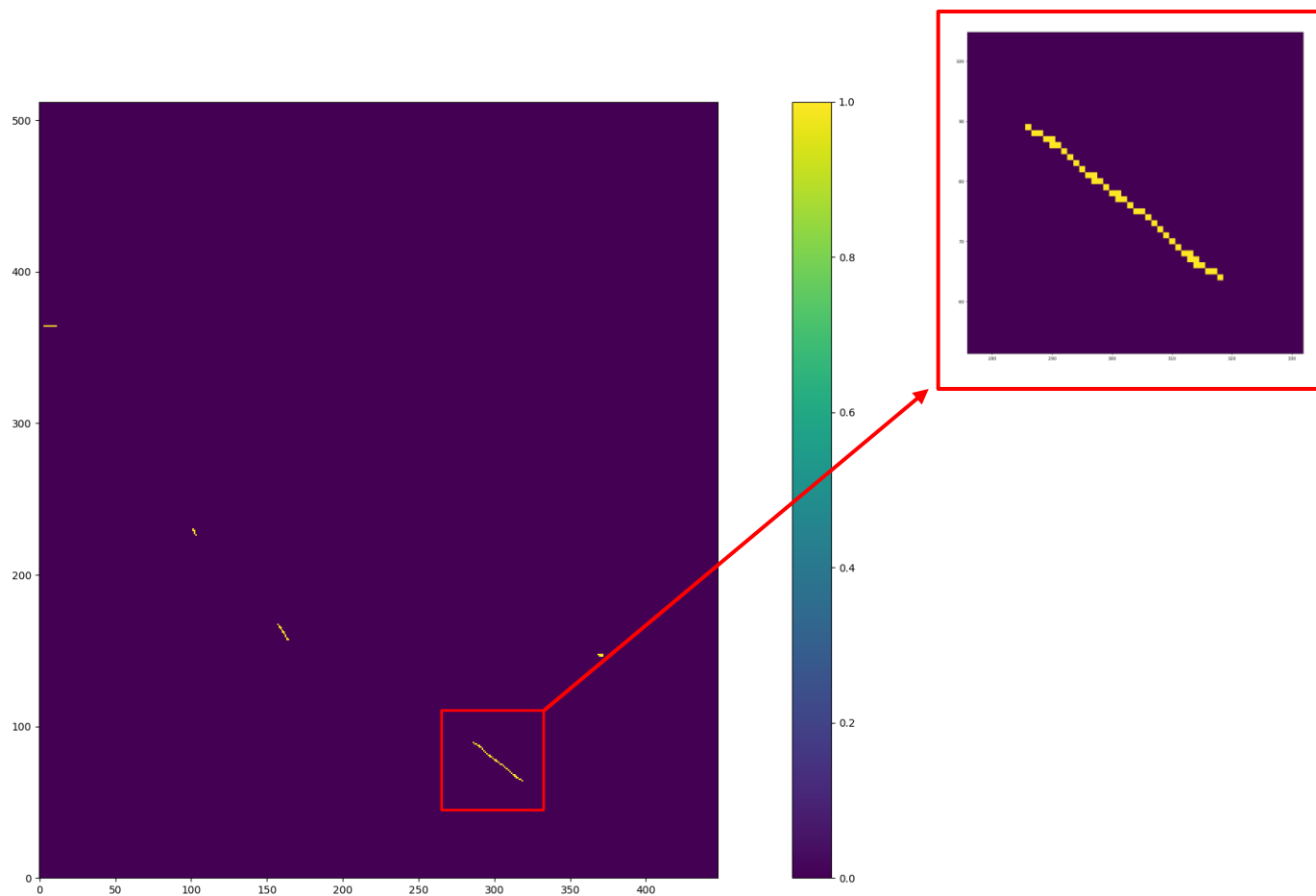


$\mu$



e

# CTPX1 – 联调测试 – 实验初步结果 – 时间分析

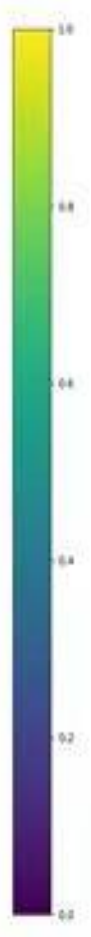
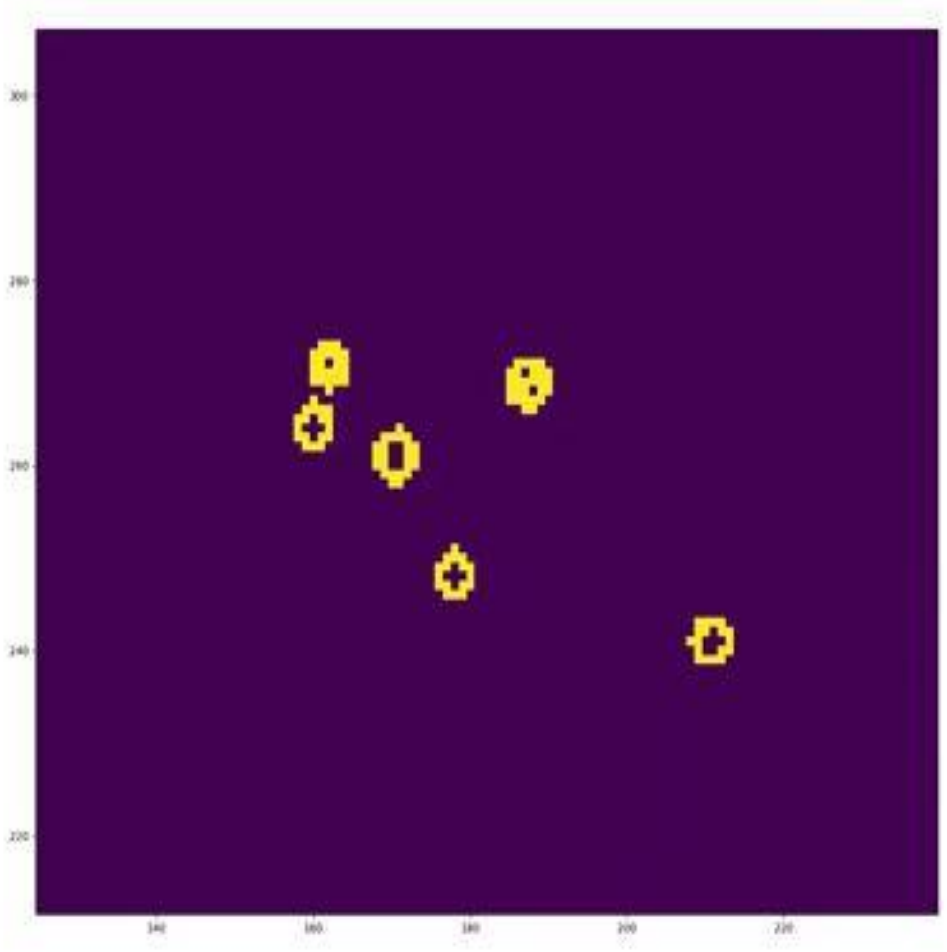
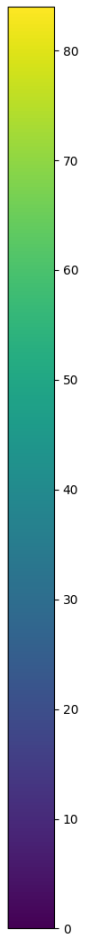
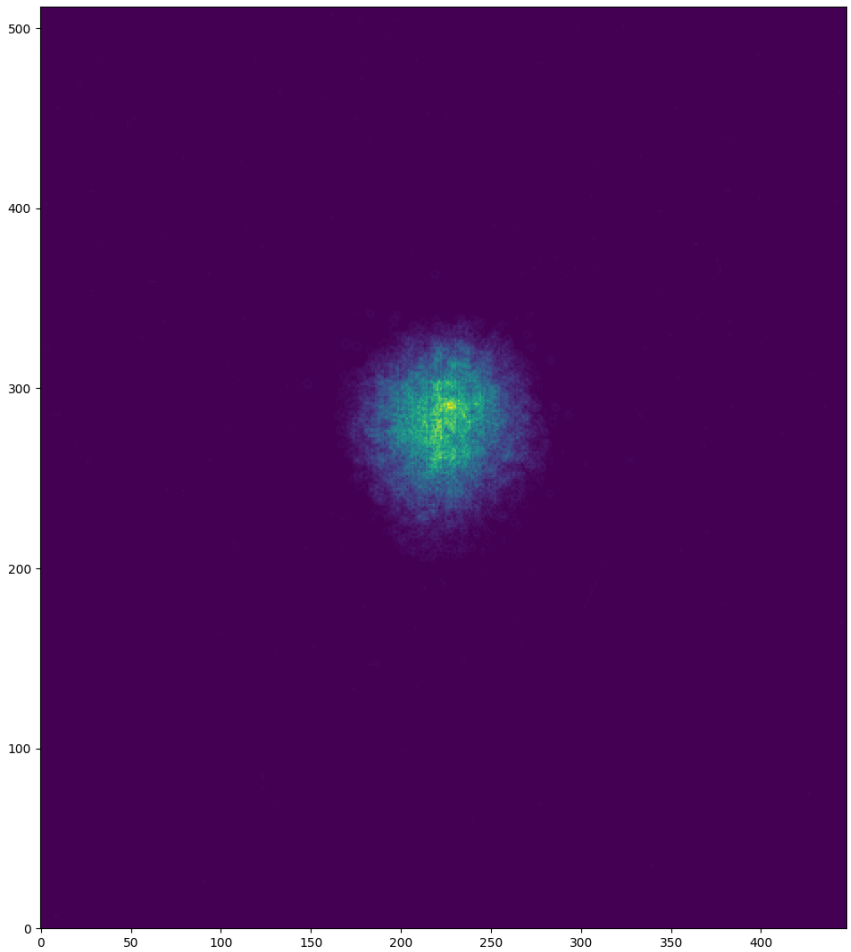


313	67	660.2421875	11.8203125
312	68	661.6875	20.5625
313	68	661.71875	2.65625
318	64	1179.140625	17.359375
293	84	2664.5234375	14.6015625
292	85	2664.578125	14.296875
298	80	8195.28125	7.40625
299	79	8196.8984375	12.2265625
294	83	8357.3046875	26.0703125
295	82	8357.34375	28.71875
314	66	8576.625	1.5
314	67	8576.9140625	5.3984375
315	66	8577.609375	12.515625
308	72	9730.2734375	13.0390625
309	71	9731.828125	17.796875
307	73	12561.7109375	10.5390625
306	74	12562.4921875	40.2578125
311	69	13260.1015625	5.4609375
310	70	13260.9921875	12.2578125
317	65	18622.40625	3.34375
316	65	18623.1015625	22.4609375
304	75	20656.078125	1.921875
305	75	20656.578125	11.234375
303	76	31925.6328125	10.1796875
302	77	31926.640625	38.984375
301	77	33384.359375	12.390625
300	78	33384.4921875	10.3828125
301	78	33385.84375	20.84375
286	89	35584.640625	26.234375
287	88	35585.2578125	15.5546875
289	87	38271.4296875	16.5078125
288	88	38271.8125	11.125
290	87	39428.6953125	5.1796875
291	86	39429.046875	24.828125
290	86	39429.609375	11.640625
296	81	40977.0078125	14.3671875
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数据分析中 .....

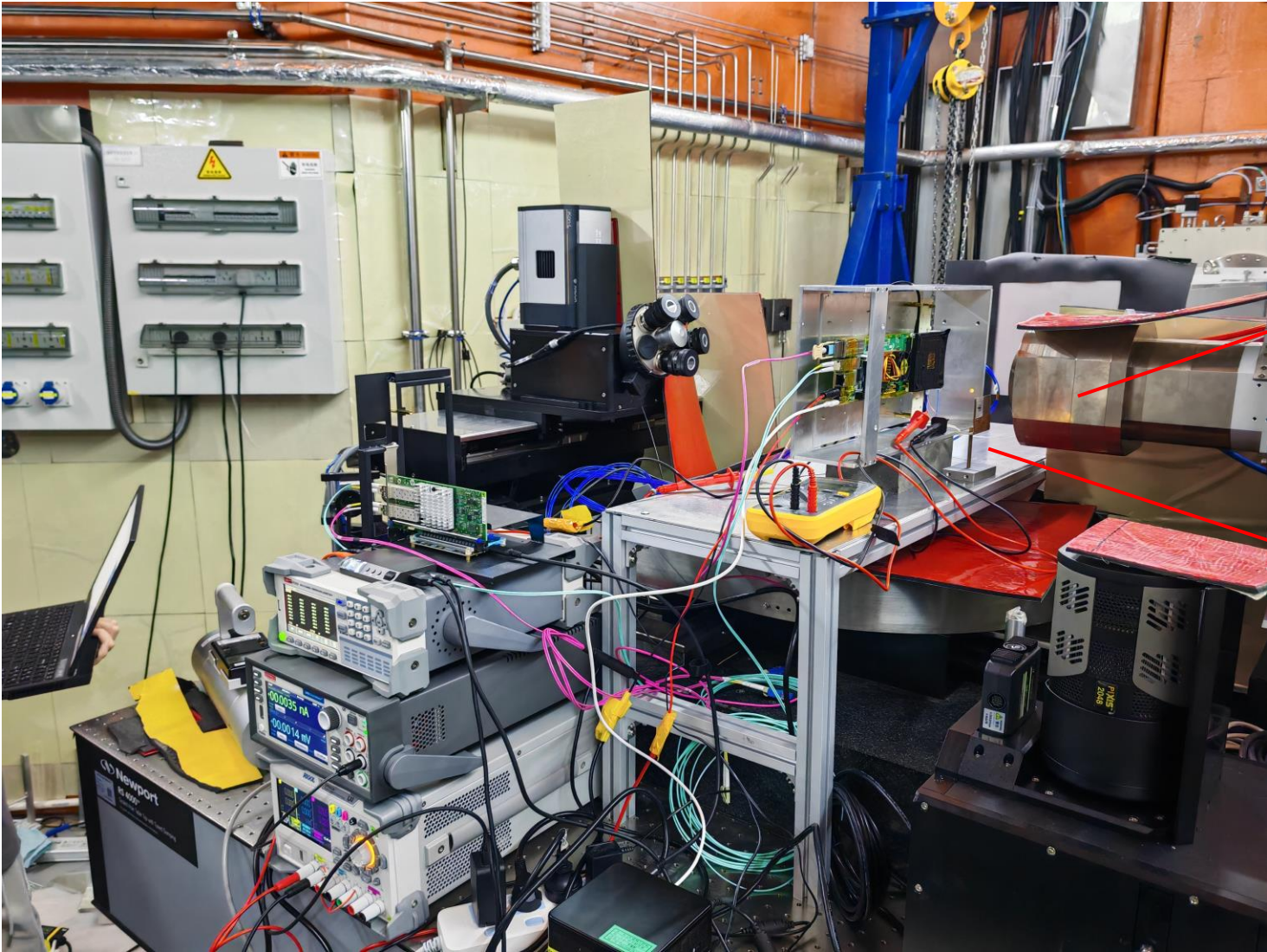


# CTPX1 – 联调测试初步结果 – $^{241}\text{Am}$ $\alpha$ 源

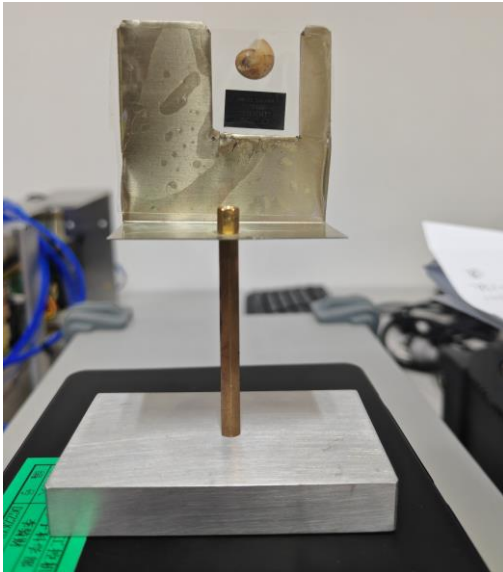


数据分析中 .....

# CTPX1 – 联调测试 – X射线 @ 2024.04



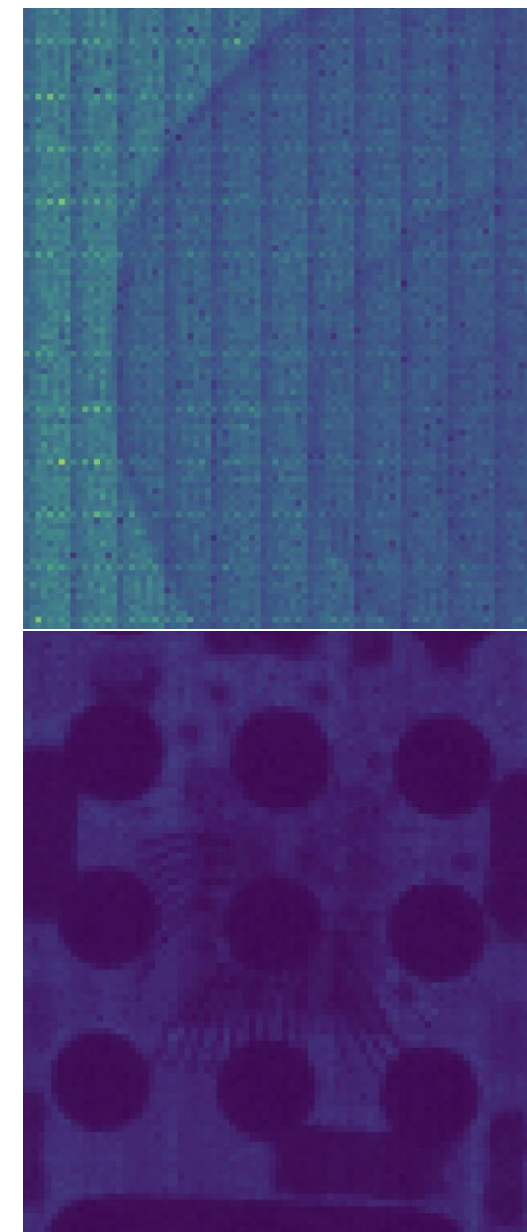
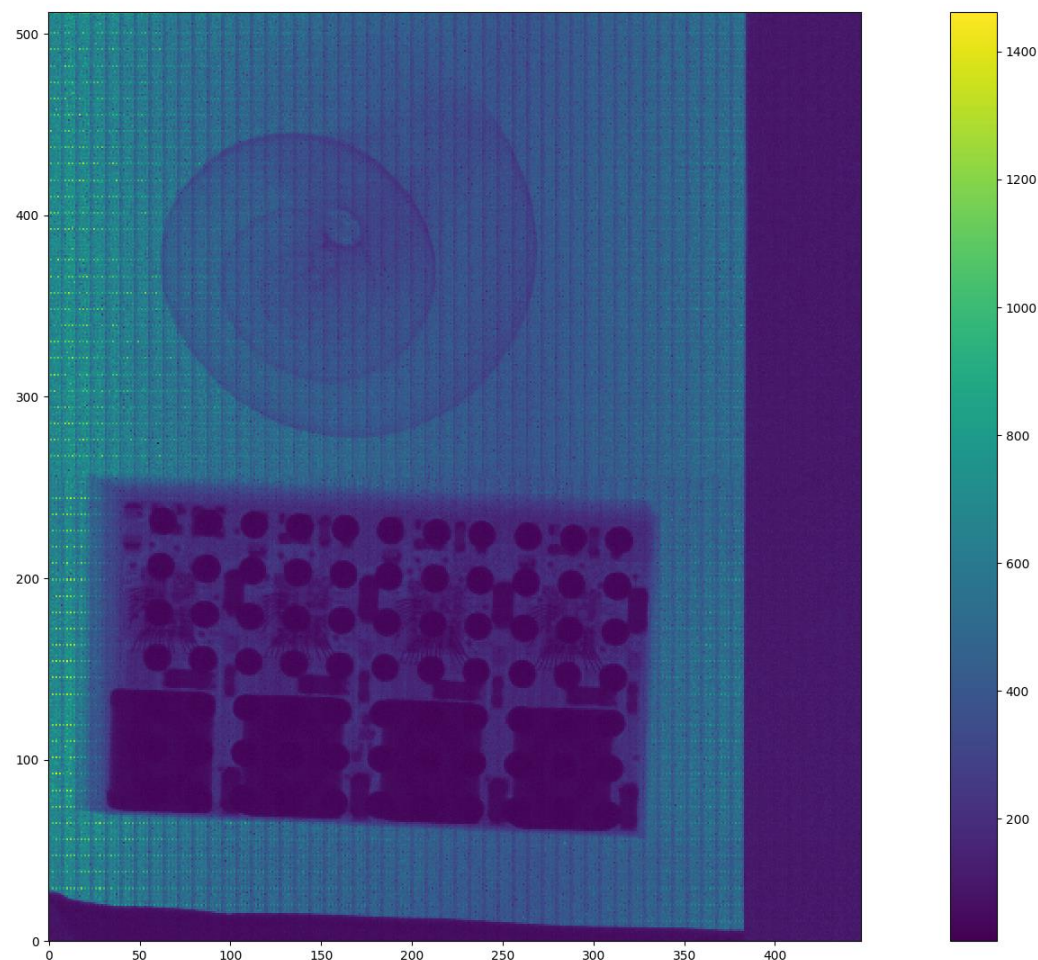
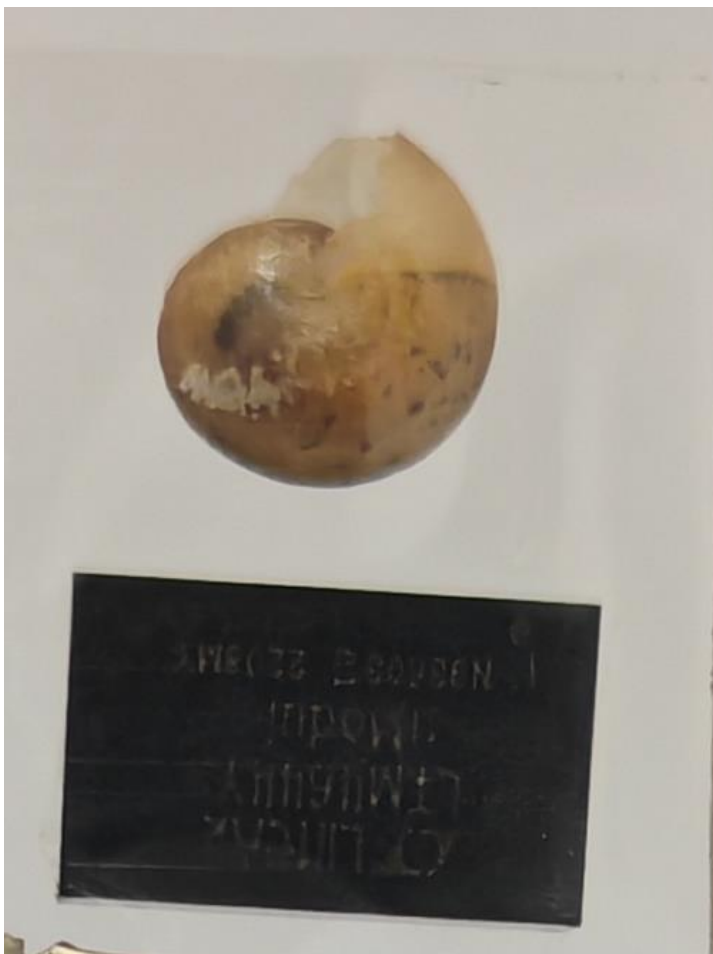
X光管



样品



# CTPX1 – 联调测试 – X射线 – 实验初步结果

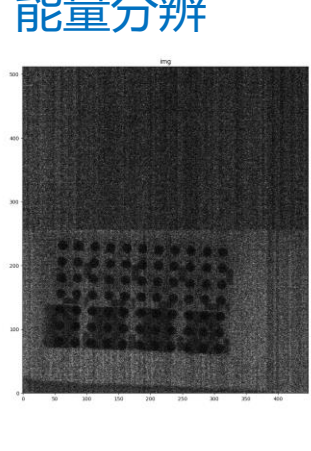


- 测试条件：传感器温度~25度，偏置70V
- X光机：钨靶，50kV，0.5W功率
- 曝光时间60秒，原始数据587.9MB（丢失90%，DAQ软件优化中）

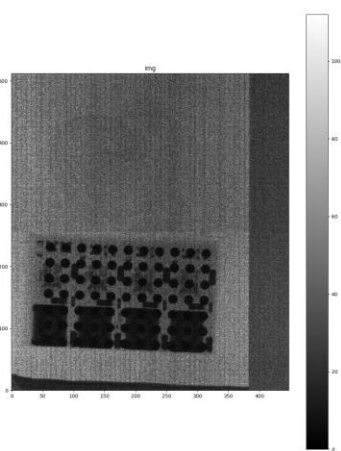
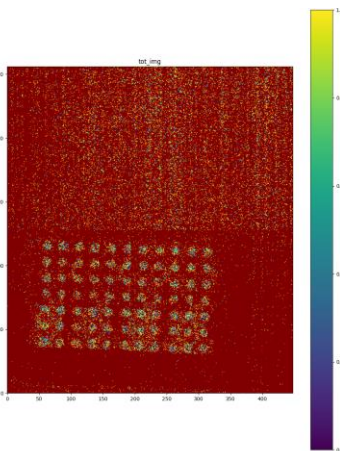


# CTPX1 – 联调测试 – X射线 – 实验初步结果

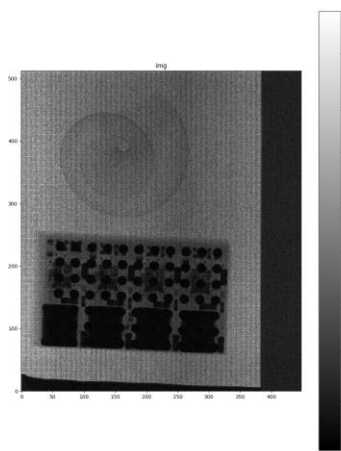
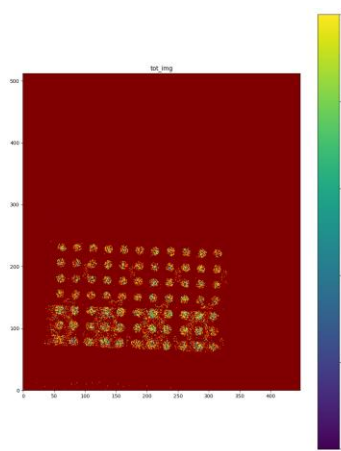
## 能量分辨



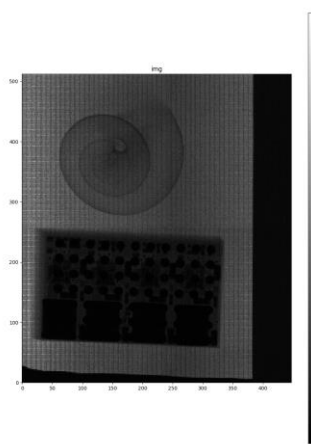
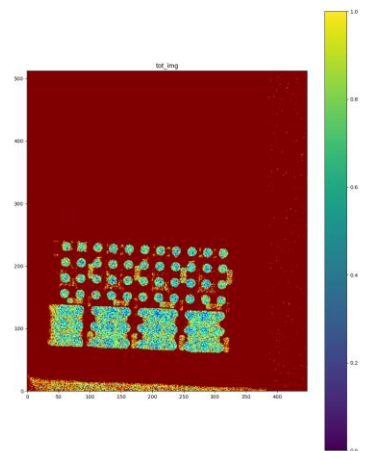
TOT > 50



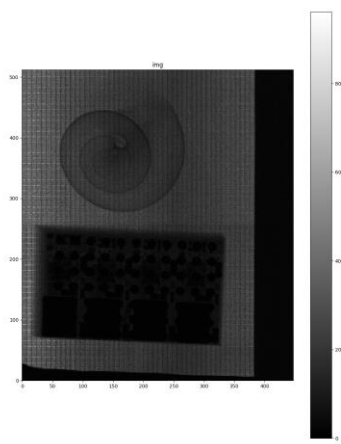
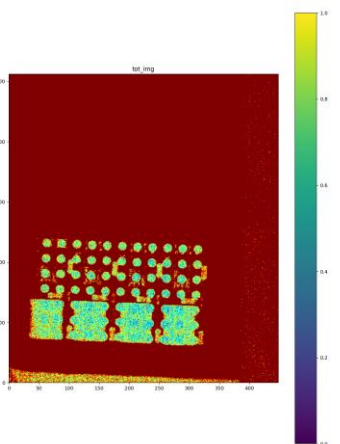
25 < TOT < 50



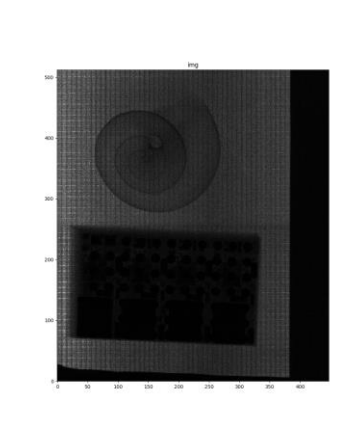
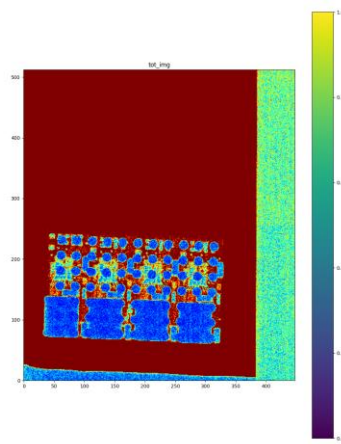
15 < TOT < 25



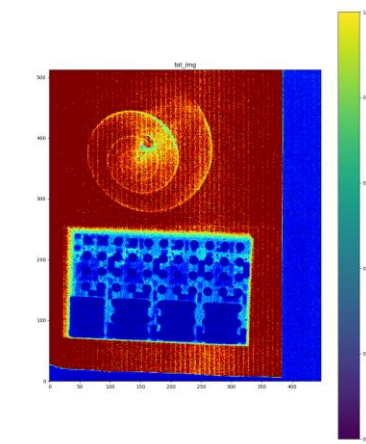
TOT < 15



TOT < 8



TOT < 4



一

研究背景简介

二

合作组及Timepix4技术介绍

三

读出电子学研制及测试进展

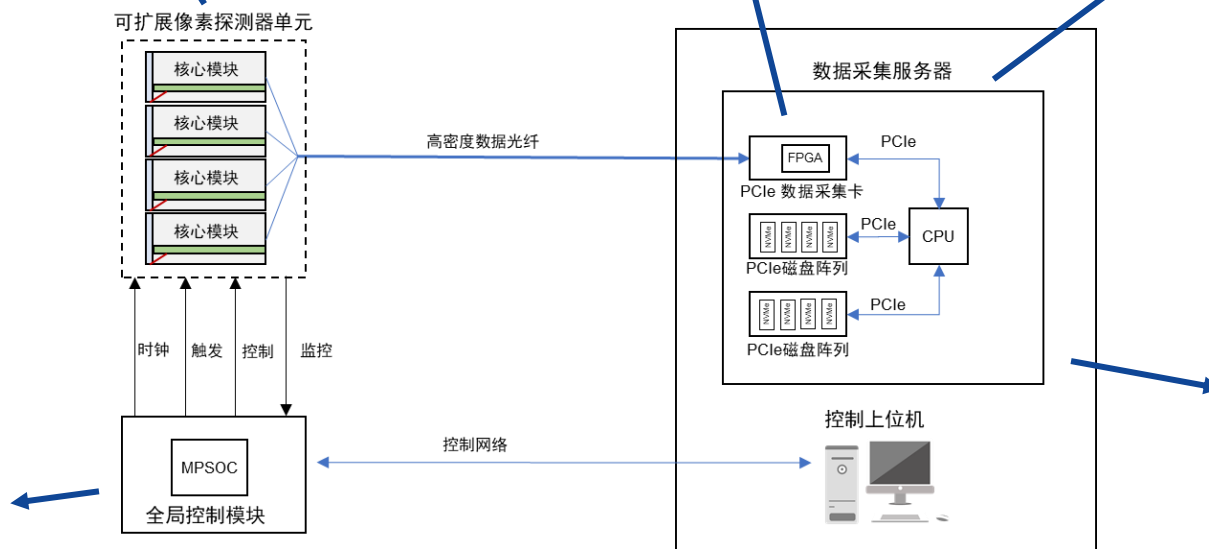
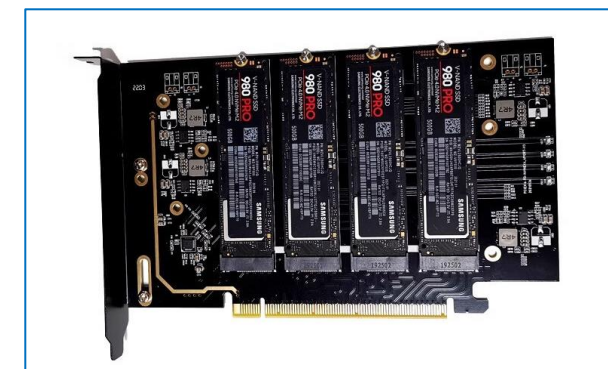
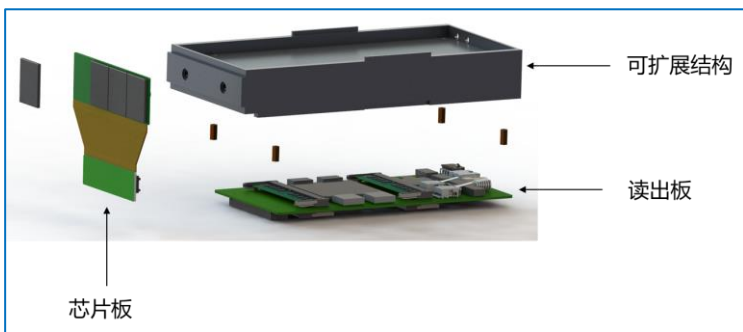
四

大面积阵列读出电子学规划

五

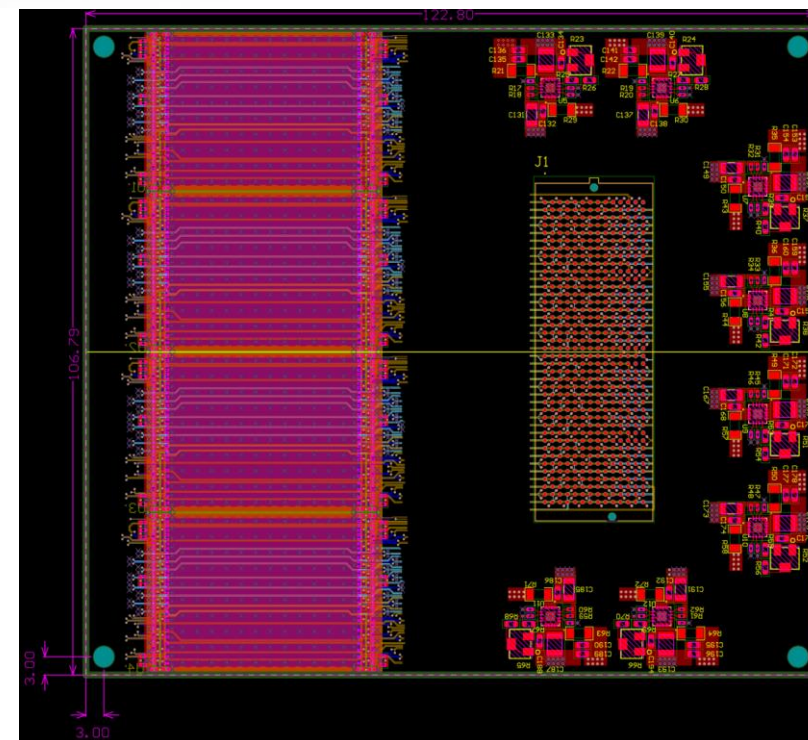
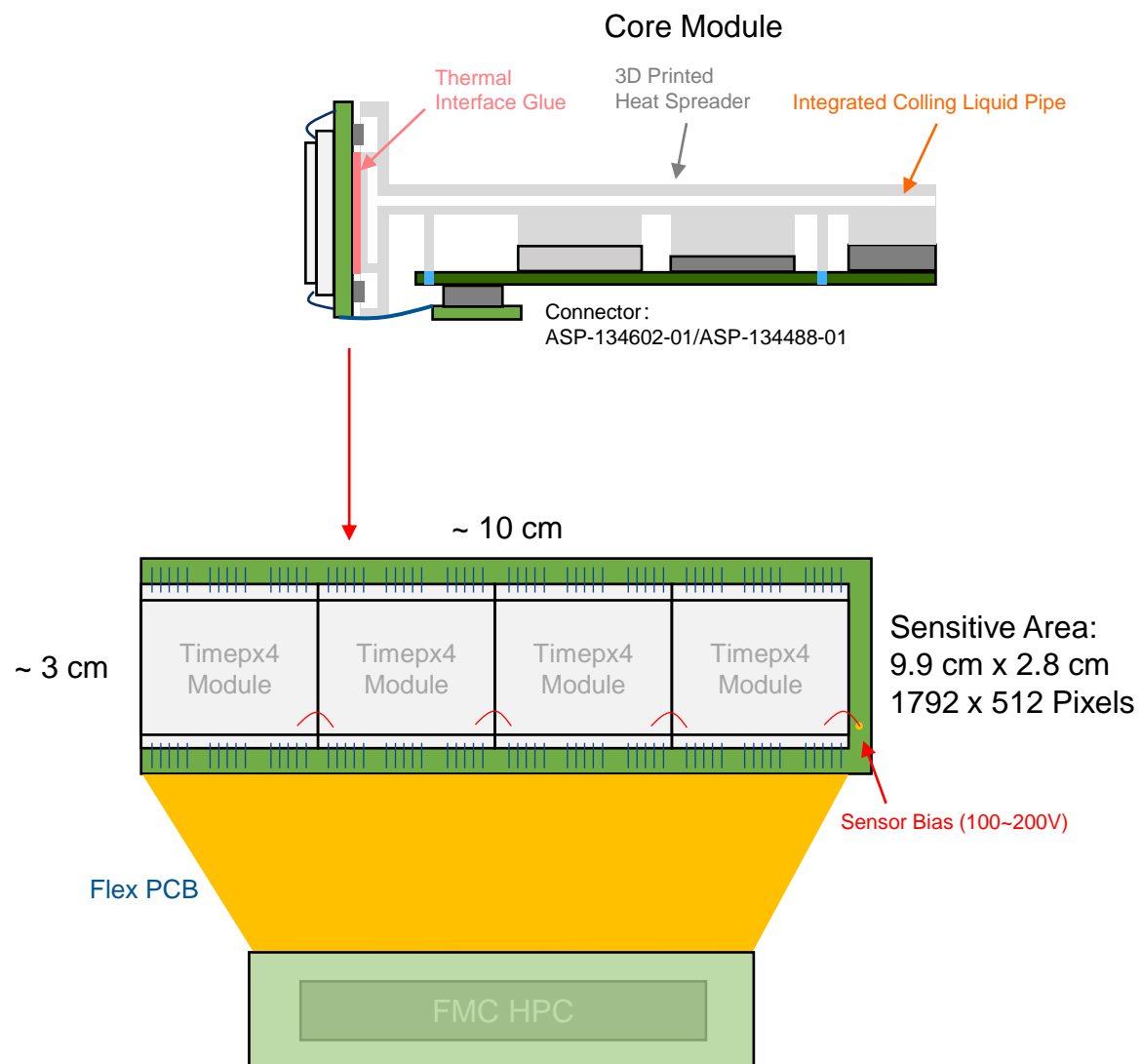
总结

# 可扩展的读出电子学系统结构

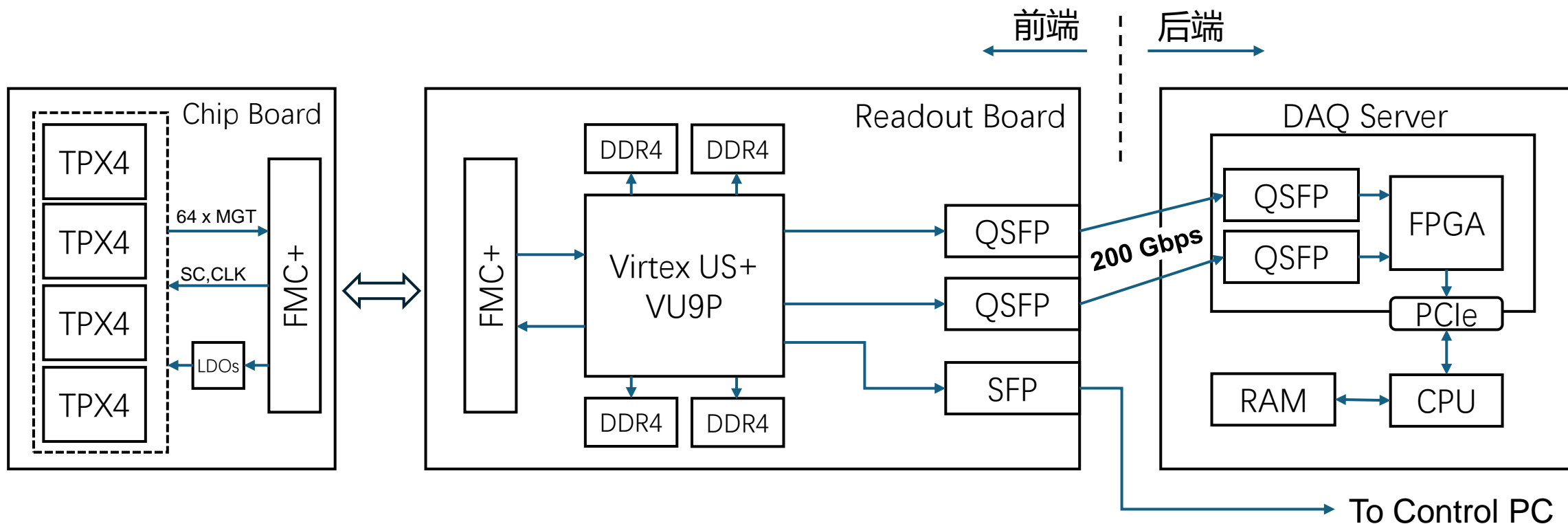




# 可扩展核心4芯片模块

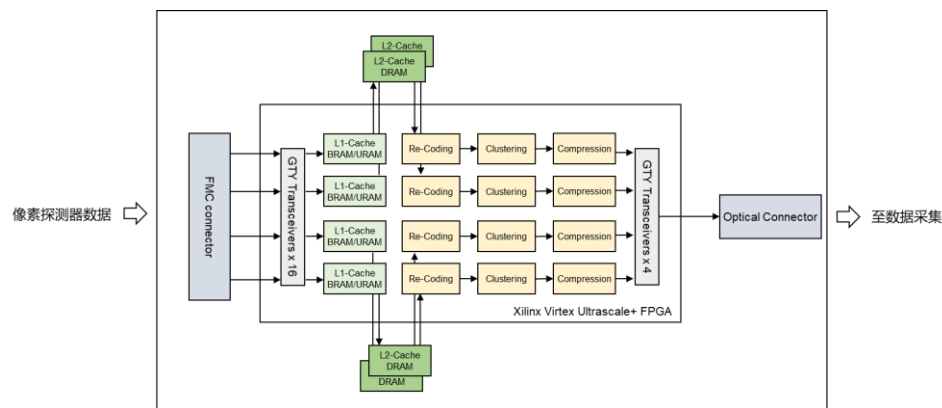


- 4模组芯片板将使用硬板进行验证，后续进行软板实施及链路测试验证



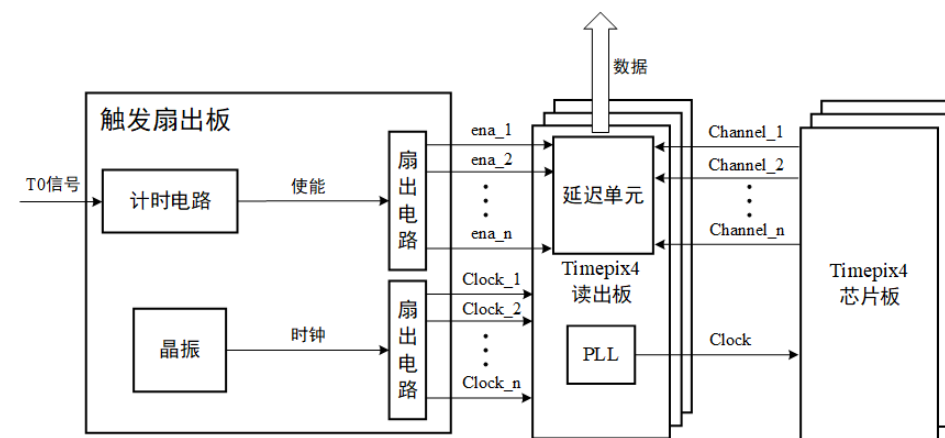
- 可扩展核心模块的电子学由芯片板+核心板组成
- 芯片板：安装4个Timepix4模组+降压LDO
- 读出板
  - 缓存4个Timepix4模组的数据（链路带宽/瞬时数据量640Gbps，平均数据量 64Gbps）
  - 基于VU9P大容量FPGA + 4 x DDR4 SODIMM + 2 x 100G QSFP
- 正在进行原理图设计中，计划下半年进行4模块联调及束流验证实验

# 走向阵列化读出电子学的难点思考

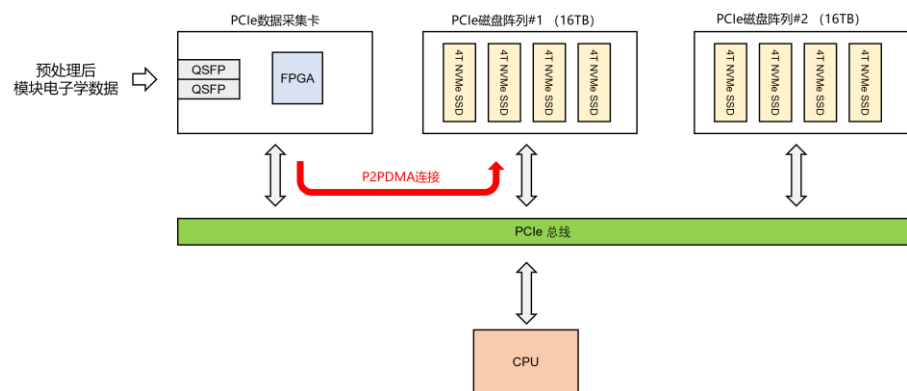


- 难点1: 数据缓存与压缩
- 解决思路: 多级缓存, 重编码, 实时聚类及压缩

- 难点2: 多模块时间同步, 如何使百皮秒级的TOA测量在大面积阵列中对齐
- 解决思路: 时钟/T0链路延时及相位的测量与补偿, VCO频率刻度



- 难点3: 海量数据无损存储
- 解决思路: 高速PCIe采集卡 + NVMe阵列卡 + P2PDMA





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研究背景简介

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合作组及Timepix4技术介绍

三

读出电子学研制及测试进展

四

大面积阵列读出电子学规划

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总结

- **面向能量分辨中子成像需求，CSNS正在基于Timepix4模组研制高速辐射成像探测器**
- **Timepix4是一种具有较高潜力的像素探测器读出芯片**
  - 55um像素尺寸、单片2.8x2.5cm探测面积，TSV设计支持四面拼接
  - 事例读出模式下可以实现200 ps时间分辨、15位TOT能量分辨
  - 帧读出模式下支持最高89kfps@8bit计数深度
- **项目团队布局了多种规模的辐射成像探测器，最终目标为20cmx20cm阵列**
  - 目前使用Si-PIN探测器：可以测量可见光\*、X射线、带电粒子等.....
  - 单模块CTPX1: 硬件研制完成，正在调试中，即将进行中子实验
  - 四模块CTPX4: 硬件设计中，预计年底进行（中子）束流实验
  - 20x20cm阵列：2025年启动研制
- **阵列化的难点：缓存、压缩、存储、时间同步**
- **应用领域：中子、X射线（天体、诊断等）、电子（透射电镜、量子关联成像等）**
- **欢迎联系我们团队(GL: 孙志嘉)，探索应用、传感器、读出电子学、散热等方面的合作**