Timepix4像素探测器读出电子学进展及在CSNS的中子成像应用

刘洪斌 (hbliu@ihep.ac.cn)
中国科学院高能物理研究所/散裂中子源科学中心

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第六届半导体辐射探测器研讨会

Institute of High Energy Physics
Chinese Academy of Sciences

China Spallation Neutron Source

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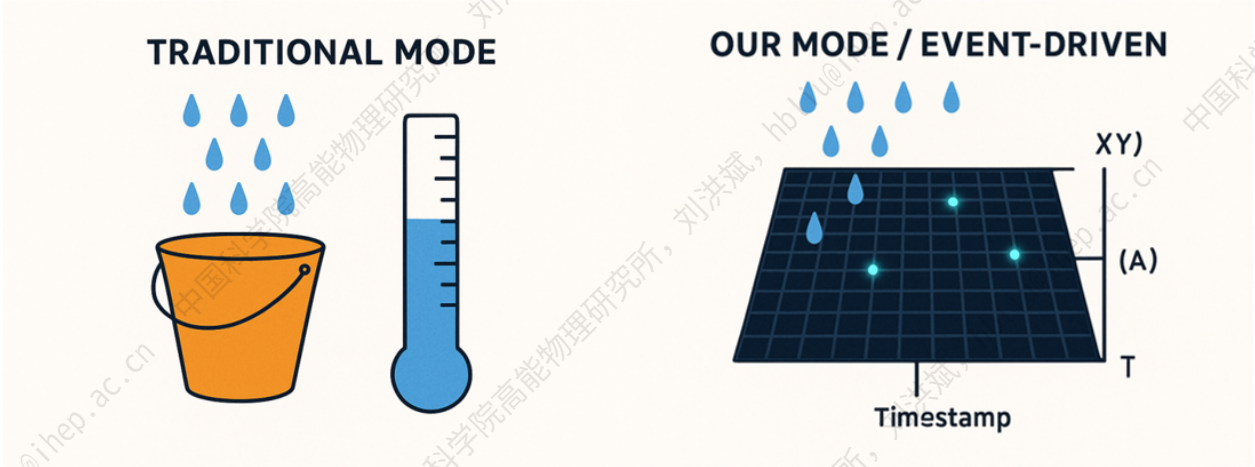
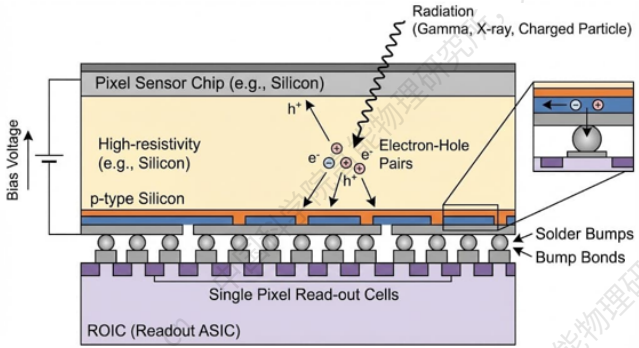
积分成像与事例成像



- 传统成像（积分模式）
- 事例成像（保留位置、时间、能量等原始信息）

事例成像的核心：复合式像素探测器

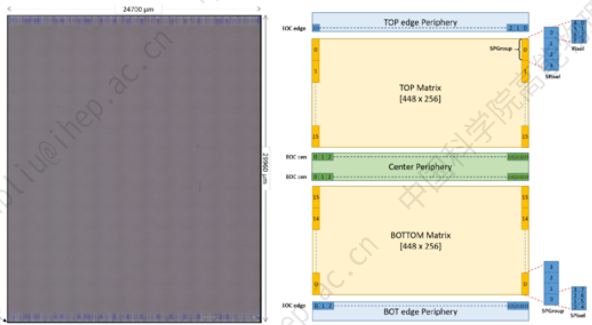


Name	Pixel Size(μm²)	Array size	Frame Rate (Hz)	nm	Operating mode
PILATUS3	172 × 172	60 × 97	500	250	Frame
Medipix3	55 × 55	256 × 256	1.5k	130	Frame
Timepix3	55 × 55	256 × 256	1.5k	250	Frame、Data-driven
XPAD3	130 × 130	80 × 120	700	250	Frame
UFXC32K	75 × 75	128 × 256	23k(@2bit)	130	Frame
BPIX3	55 × 55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

- 事例成像技术的核心：一种能对辐射进行高速、多维信息测量的复合式像素探测器
- Timepix4是由Medipix4合作组研制的最新一代事例型像素探测器读出芯片

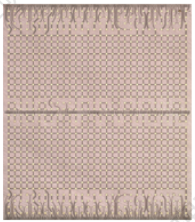
Timepix4: 一种复合式像素探测器读出芯片

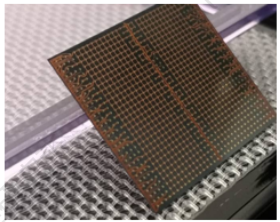
			Timepix3 (2013)	Timepix4 (2019/20)	
Technology			IBM 130 nm – 8 metal	TSMC 65 nm – 10 metal	
Pixel size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable (TSV) 512 x 448	3.5 x
Sensitive area			1.98 cm^2	6.94 cm^2	
Readout modes	Data driven (tracking)	Mode	ToT and TOA		
		Event packet	48-bit	64-bit	
		Max rate	< 43 Mhits/cm^2/s	357.6 Mhits/cm^2/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/cm^2/s	~ 800 Ghits/cm^2/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^-	



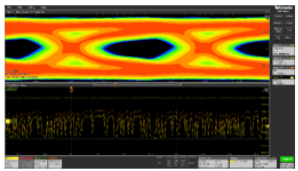
关键参数

- 输入信号：电信号，最低阈值500电子
- 像素尺寸：55 x 55 um
- 像素数量：512 x 448 （23万像素）
- 探测面积：6.94 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/cm^2/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/cm^2）
- 连接sensor：倒装焊
- 连接PCB：WB（两边），TSV（两边+中间）





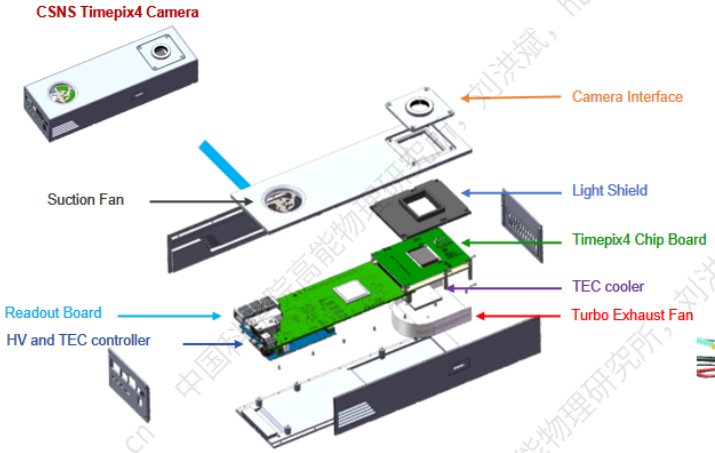
Timepix4 with TSV



5G PRBS through TSV

- **IHEP/CSNS 2022年加入Medipix4合作组，开始基于Timepix4研制高速辐射成像系统**

事例型高速辐射成像系统CTPX1



CSNS CTPX1 高速辐射成像系统

- 单模组全速度读出 (**16 x 5.12Gbps links**)
- 基于Xilinx Zynq Ultrascale+ ZU15EG FPGA
- 多级缓存设计，**极限计数率1.2Gcps**
- 集成内部高压产生/监控，以及半导体温控系统

80Gbps/ 1.25Gcps/32GB buffer → **64Gbps/ 800Mcps/32GB buffer** → **32Gbps/400Mcps/1T buffer**

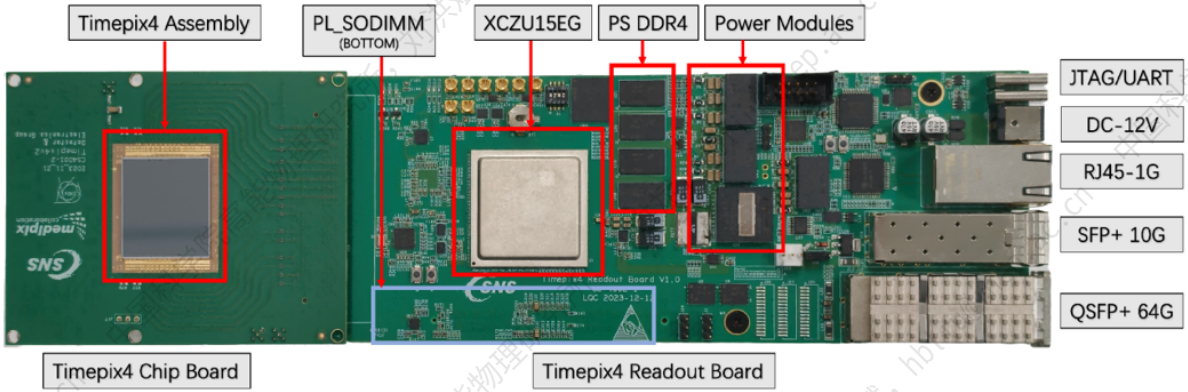
Timepix4 Chip Board and Readout Board

Readout links

PCIe Readout Card

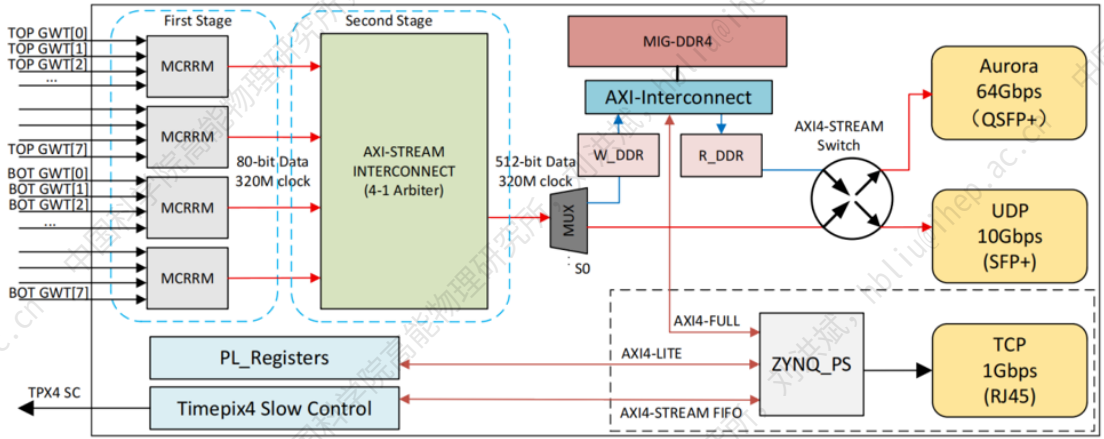
PCIe连接

高速读出电子学

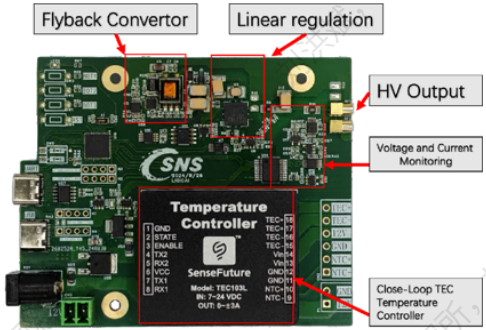


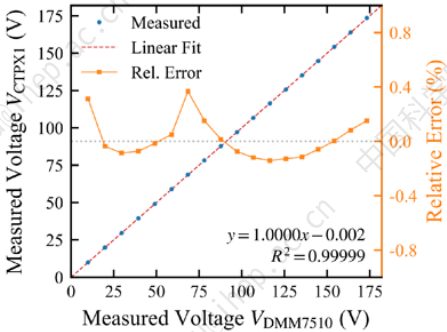
- **基于Zynq Ultrascale+ ZU15EG的单模块全带宽读出电子学**
  - 16 x 5.12Gbps GWT link readout
  - DDR4 SODIMM as peak event buffer
  - FreeTOS on PS side for slow control
  - 10G UDP / QSFP 64G readout

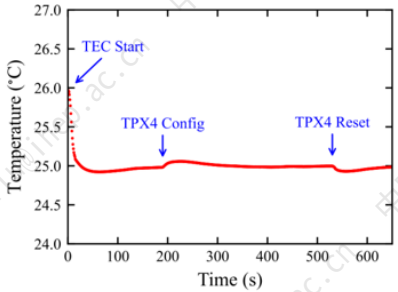
读出电子学FPGA固件结构

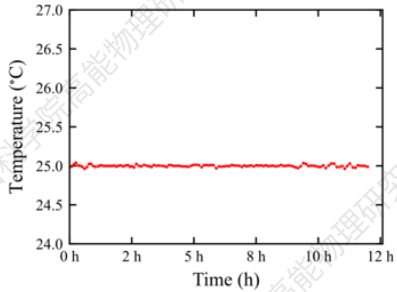


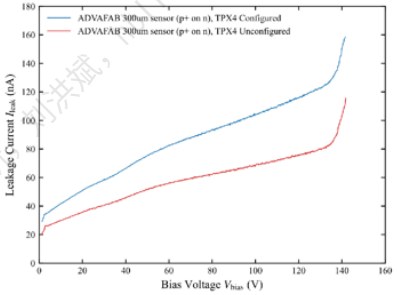
温控与集成偏置高压


Flyback Convertor
Linear regulation
HV Output
Voltage and Current Monitoring
Close-Loop TEC Temperature Controller
Temperature Controller
SenseFuture


Measured
Linear Fit
Rel. Error
$y = 1.0000x - 0.002$
$R^2 = 0.99999$
Measured Voltage V_{CTPX1} (V)
Measured Voltage $V_{DMM7510}$ (V)
Relative Error (%)


TEC Start
TPX4 Config
TPX4 Reset
Temperature (°C)
Time (s)


Temperature (°C)
Time (h)


ADVAFAB 300um sensor (p+ on n), TPX4 Configured
ADVAFAB 300um sensor (p+ on n), TPX4 Unconfigured
Leakage Current I_{bias} (nA)
Bias Voltage V_{bias} (V)

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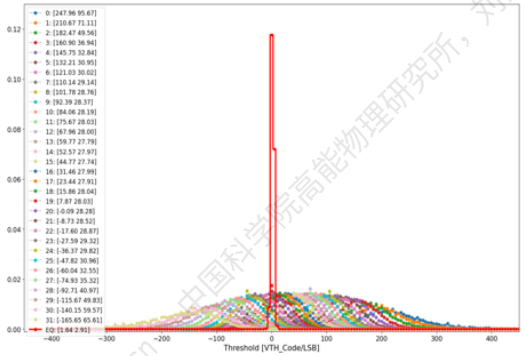
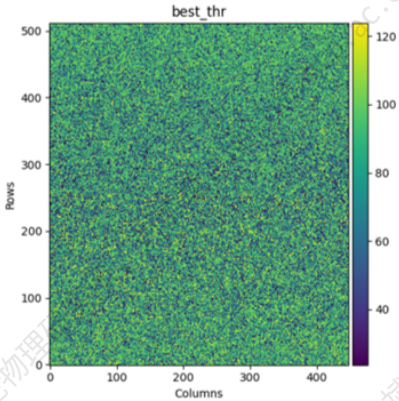
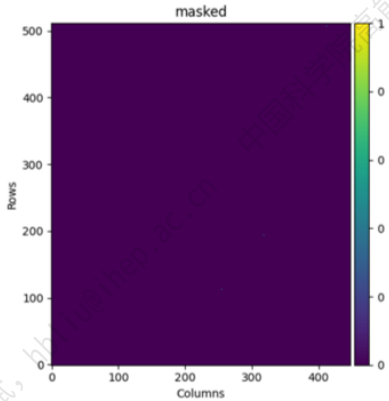
阈值调节

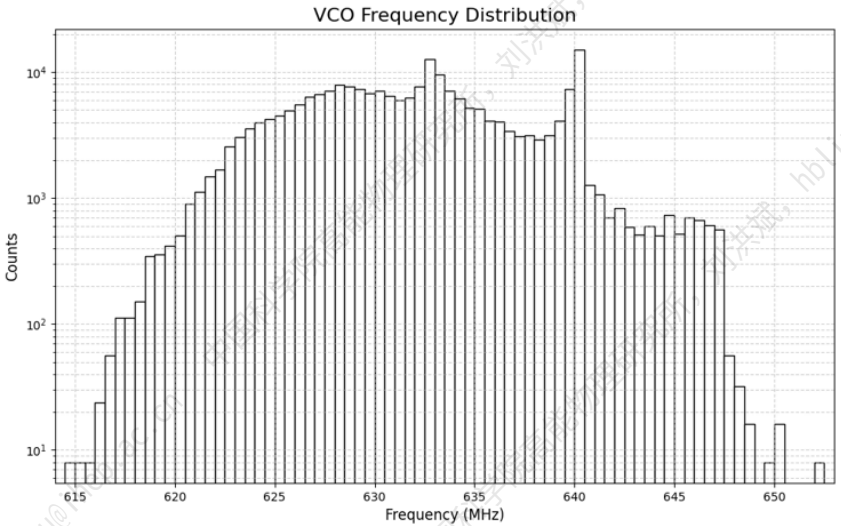


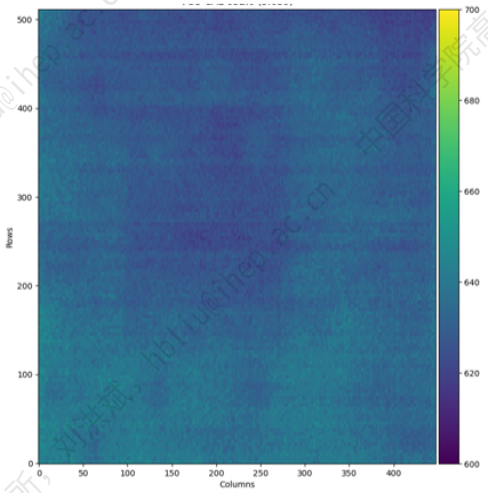




- **需要对23万个像素的阈值进行逐一校准，提升均匀性**
  - 校准后阈值分布小于50个电子（std）
  - 最小可用阈值约~500电子
  - 对于GradeA的芯片，<0.01%像素无法调节，需要屏蔽

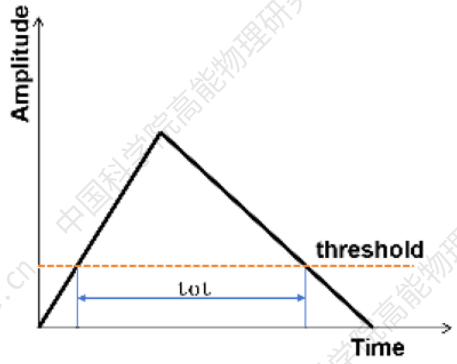
时间刻度



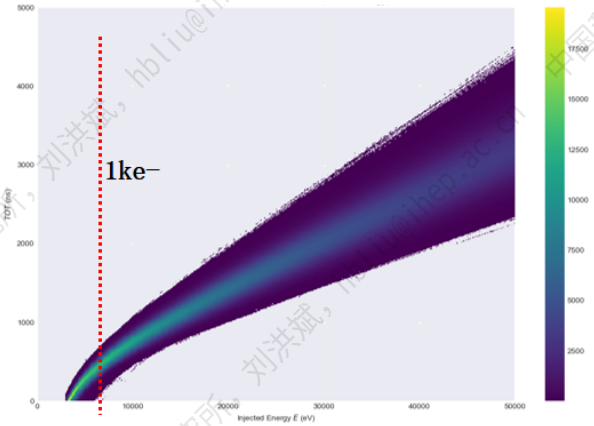


- 整个芯片使用了28672个VCO，由于工艺会导致频率偏差，引起时间测量不一致
- 通过标准参考信号，完成了对所有VCO的频率校准

能量刻度原理

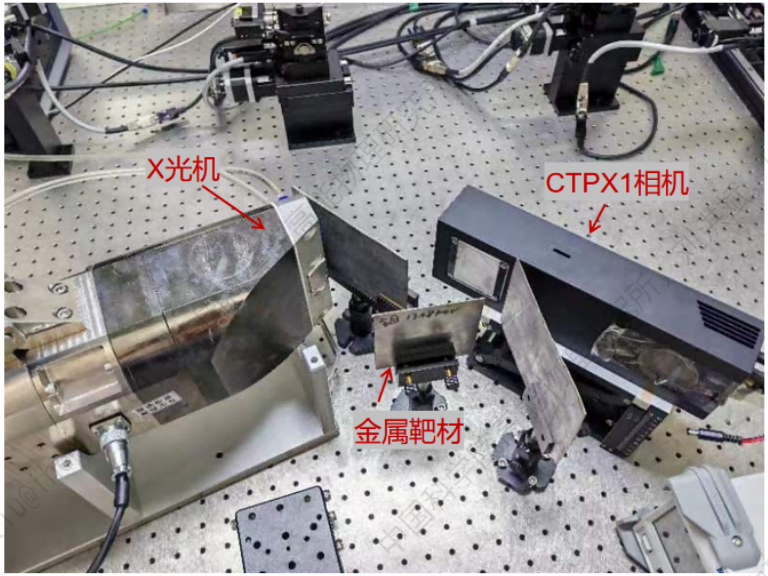


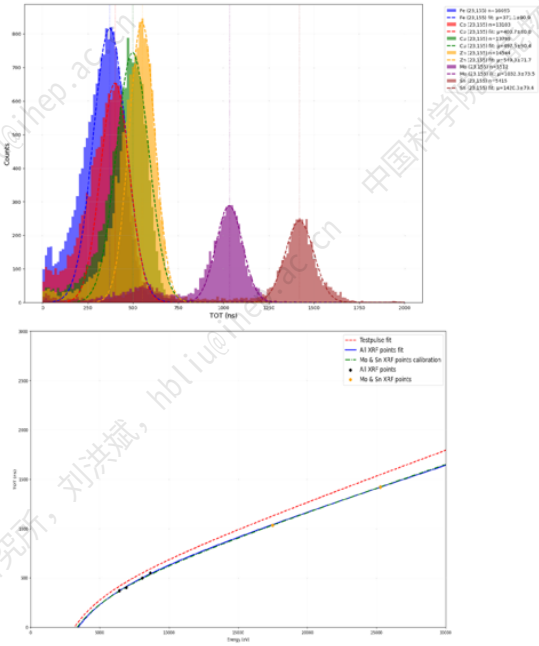
$$ToT = p_0E + p_1 - \frac{p_2}{E - p_3}$$



- 由于工艺偏差，像素间能量测量会有较大误差，需要刻度
- 使用电荷注入脉冲进行初步刻度，像素间刻度曲线偏差较大

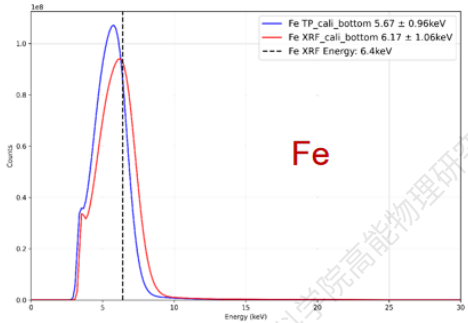
能量刻度 - XRF方法

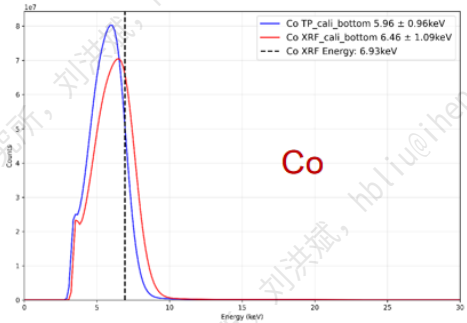


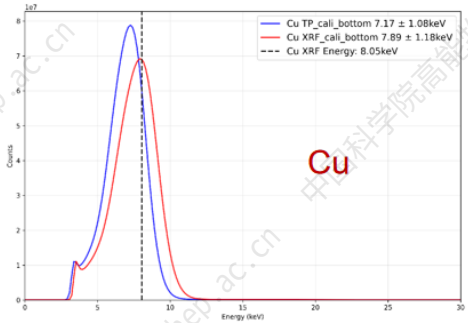


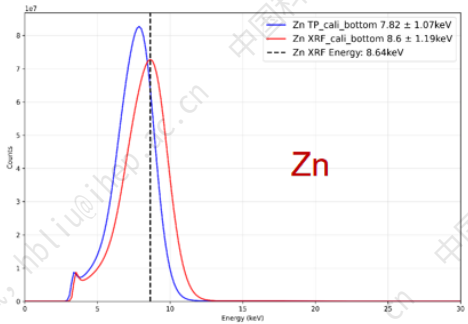
- 使用多种金属元素的特征X射线荧光峰，对23万个像素的TOT-能量刻度曲线进行了逐个修正

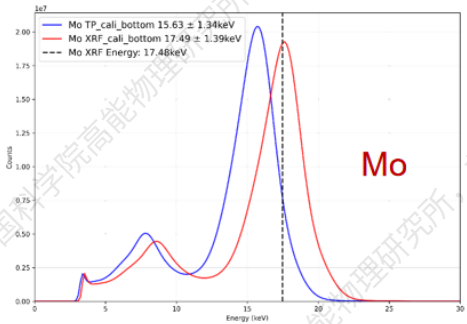
能量刻度结果

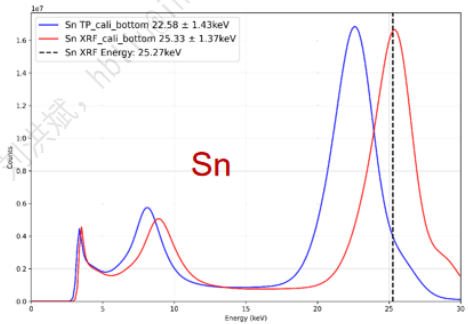






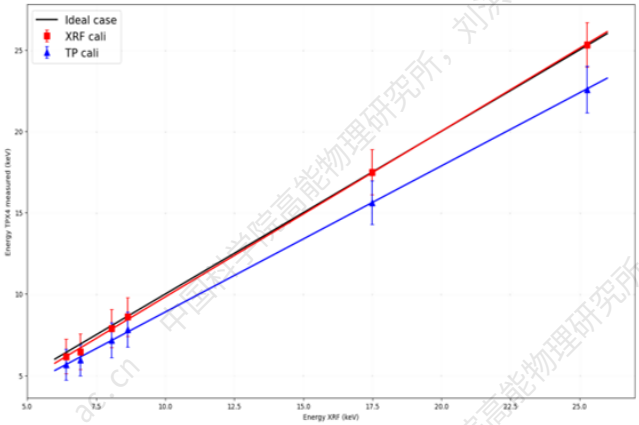






- **使用修正后的刻度曲线，可以重建6种XRF测量的能谱**

CTPX1系统刻度 - 能量刻度结果



Material	E_XRF [keV]	TP cali [%]	XRF cali [%]	XRF energy resolution [%]
Fe	6.4	11.4	3.6	40.46
Co	6.93	14.0	6.8	39.74
Cu	8.05	10.9	1.9	35.22
Zn	8.64	9.5	0.5	32.59
Mo	17.48	10.6	0.1	18.72
Sn	25.27	10.6	0.2	12.74

- 初步结果显示，事例成像的重建能谱，能量分辨可以达到12.7% @ 25 keV左右
- 进一步优化刻度与聚类算法，可以进一步能量分辨

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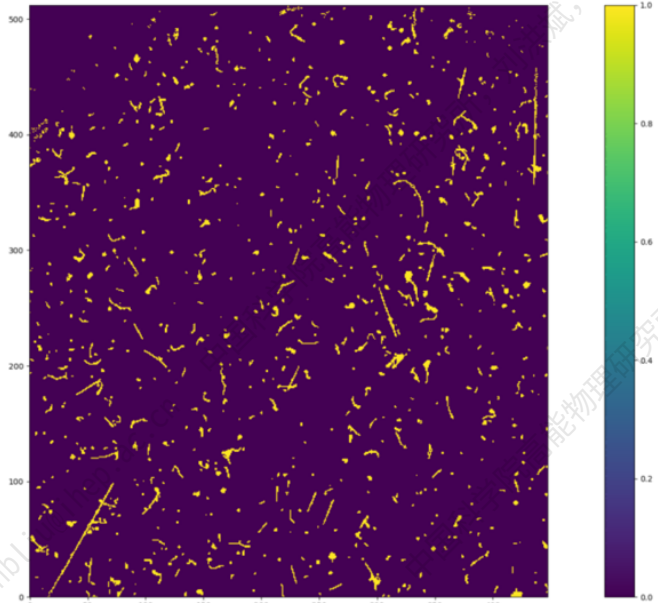
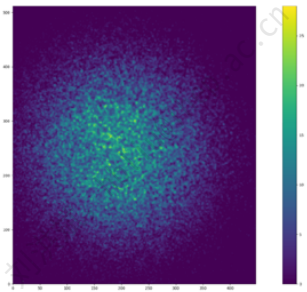
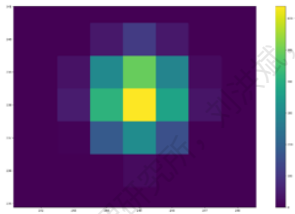
验证性实验 - 宇宙线/放射源



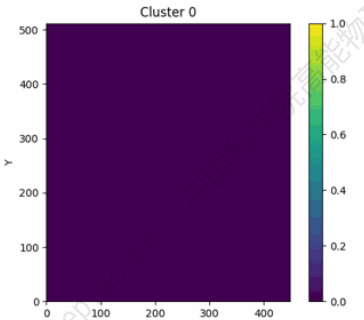
30min cosmic



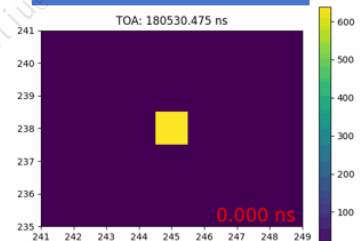
60s Am241 exposure



Alpha event TOT

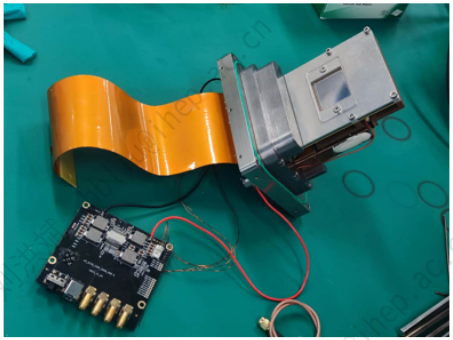


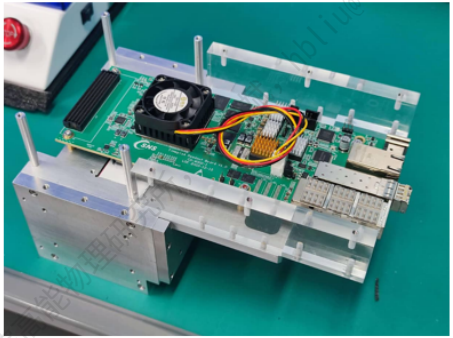
500 α events



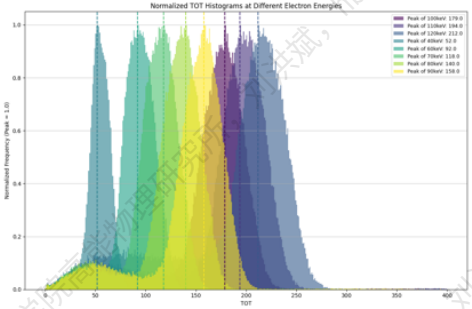
Alpha event TOA

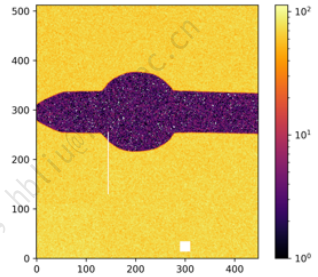
验证性实验 - 电子

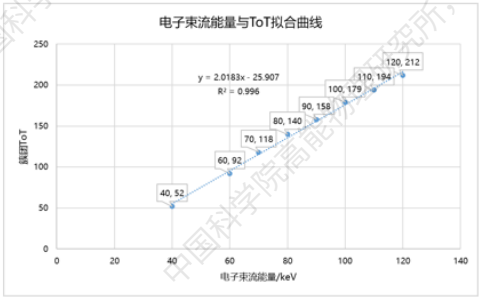


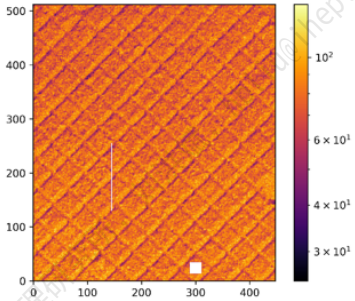


验证性实验 - 电子



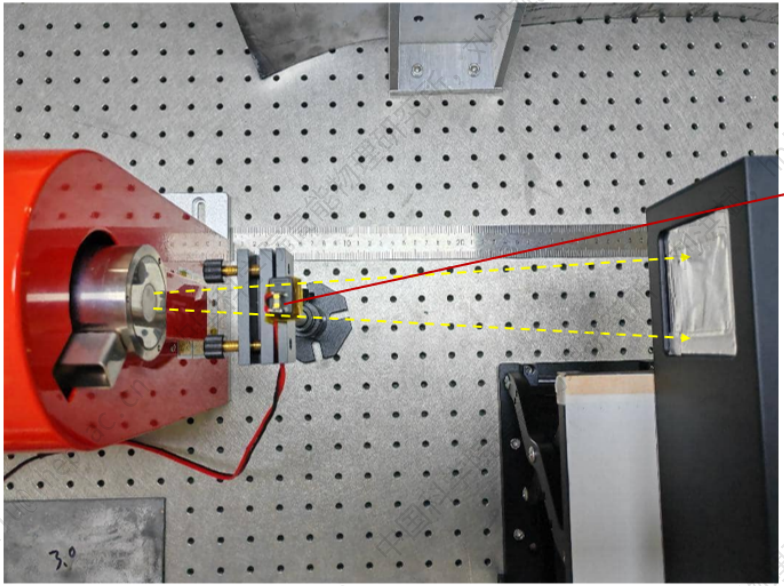






- 对40keV - 150keV的电子束流响应进行了实验验证

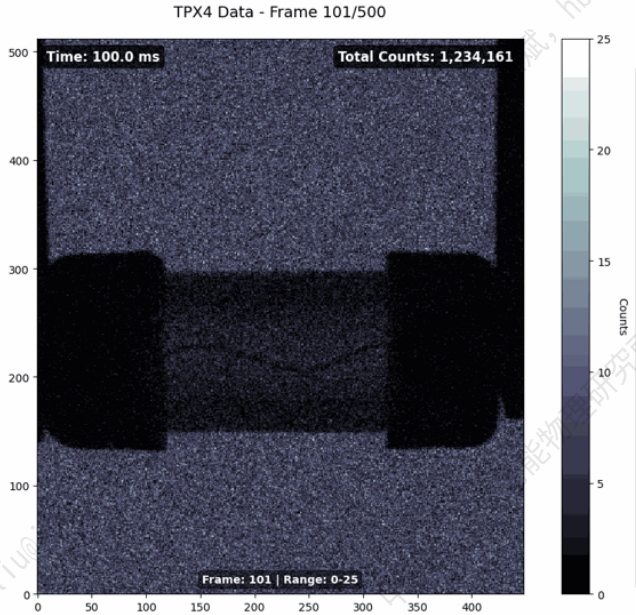
验证性实验 - 高速X射线成像

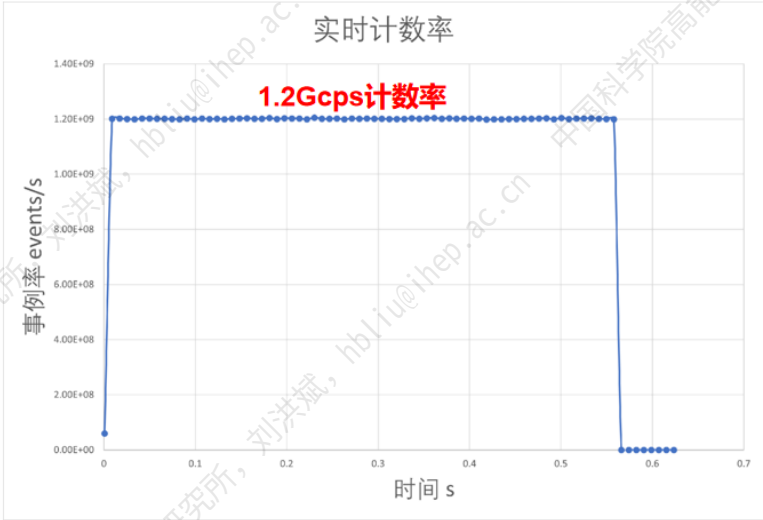


实验设置

- 滨松微焦点源 L12161-07
- X 射线源高压：70KeV
- X 射线源电流：300uA
- 靶材：Wu
- Sensor 高压：40V
- 数据获取方式：事例驱动
- 取数方式：相机0.5S 缓存读出

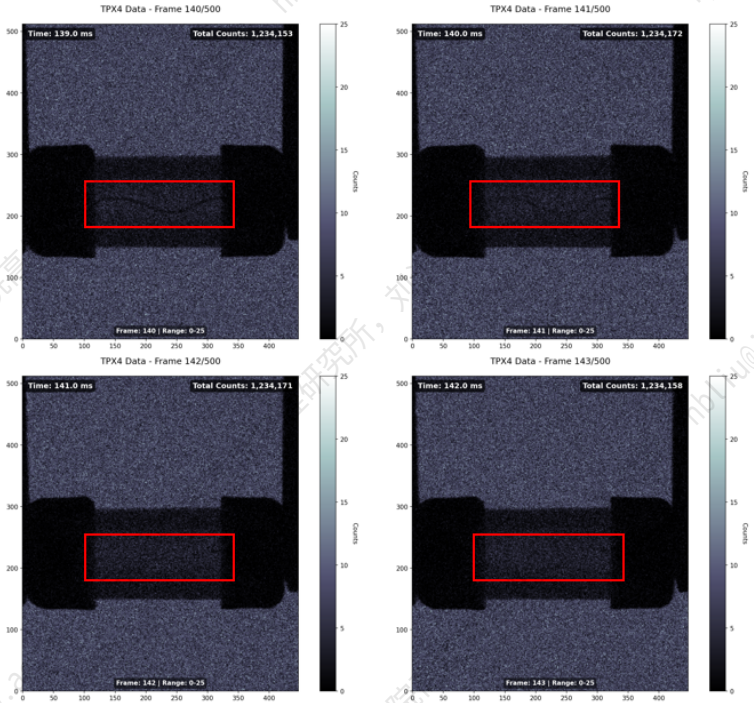
验证性实验 - 高速X射线成像



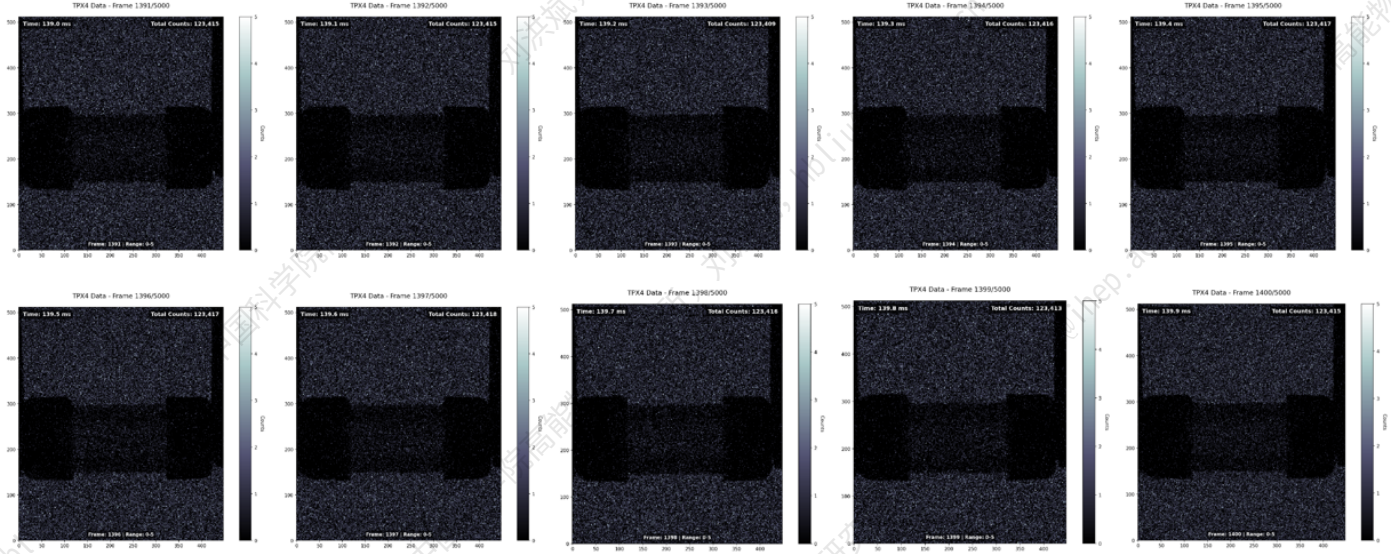


- 基于原始事例（X,Y,TOA,TOT）重建1000fps动态图像，对应事例率1.2Gcps
- 单帧包含1.23Mevent，对应100Mb文件大小（80bit事例）

验证性实验 - 高速X射线成像

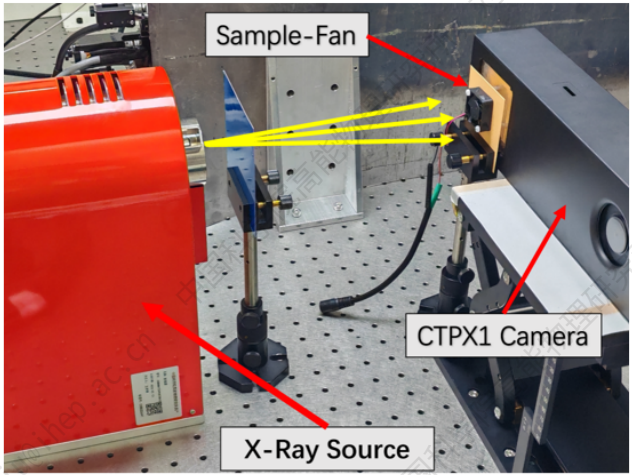


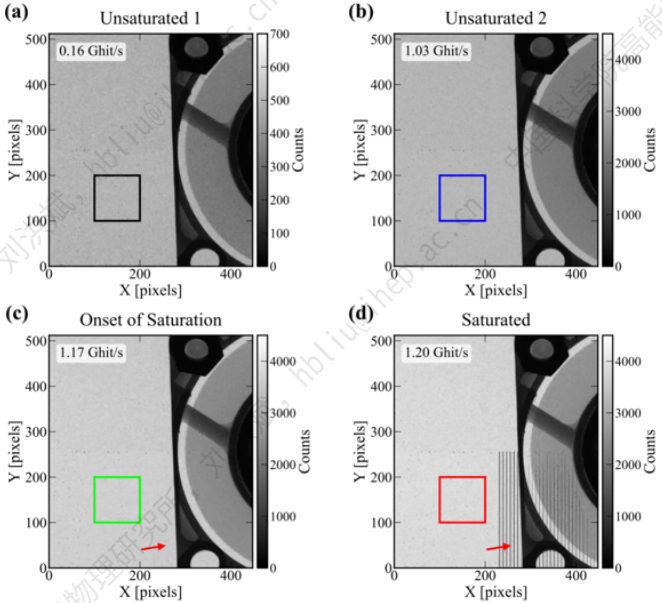
验证性实验 - 高速X射线成像



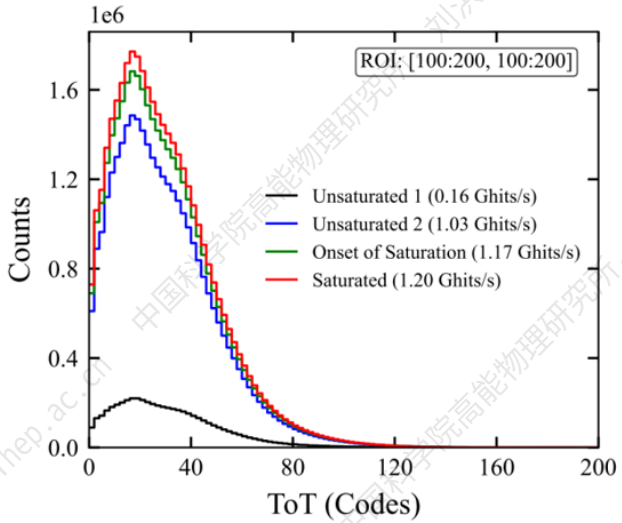
- 重建10000fps动态图像，单帧100us，但是信噪比太低，难以看清楚过程
- 下一步实验：ROI（屏蔽像素），以及帧读出模式

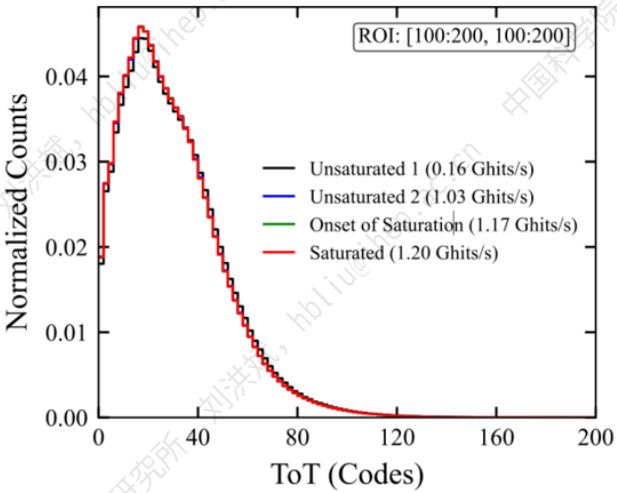
验证性实验 - 高速X射线成像





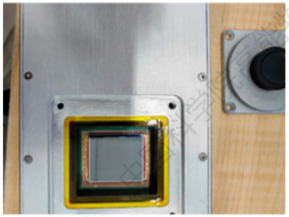
验证性实验 - 高速X射线成像

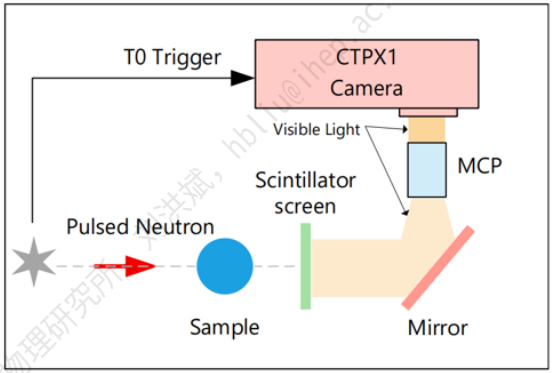




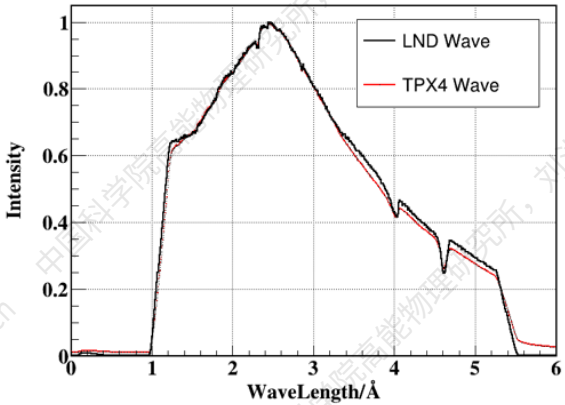
验证性实验 - 能量分辨中子成像

CSNS energy resolved neutron imaging detector with a CSNS timepix4 camera





验证性实验 - 中子飞行时间测量

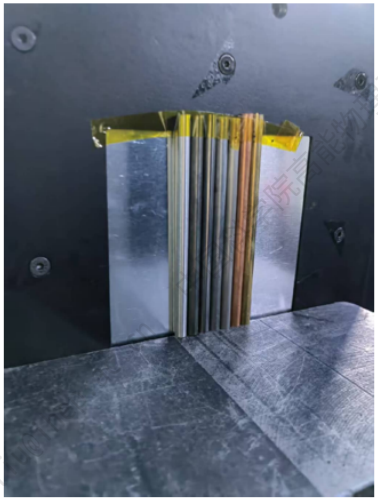


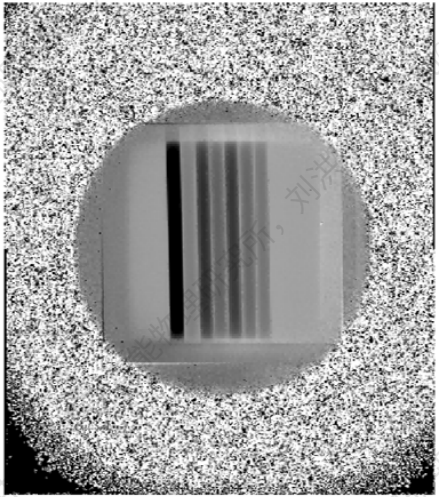
- Scintillation Screen: ZnS
- Lens: Schneider F2.2/50mm
- Zoom:0.1375x
- Img.Int. Gain:3600
- Test Time: 30min

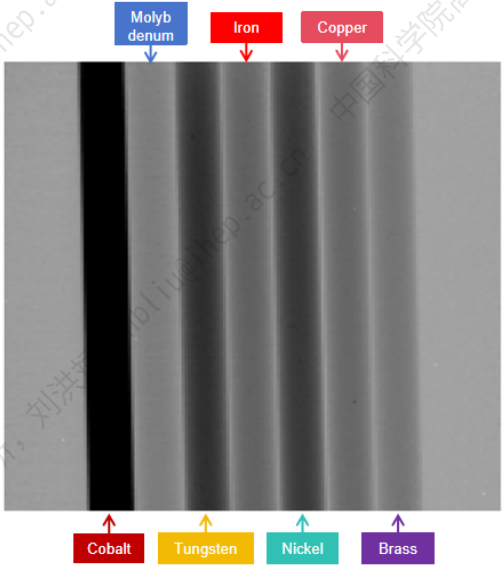
- **测量到的中子飞行谱与标准氦3管探测器一致（LND PSD）**

验证性实验 - 中子成像实验

- Sample: 7 x metal rods
- Lens: Schneider F2.2/50mm
- Scintillation Screen: ZnS
- Zoom: 0.1375x



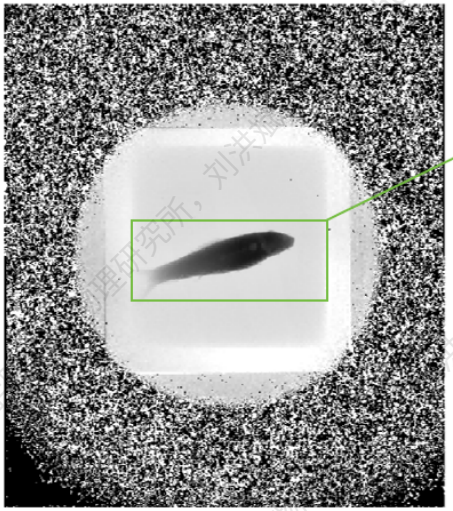


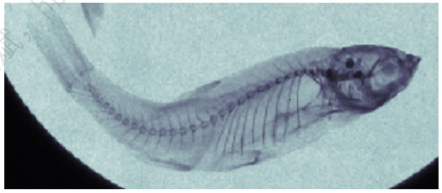


- FOV ≈ 100mm×100mm
- 可以通过能量选择进行成像

验证性实验 - 中子成像 vs X射线成像

- Sample: Fish
- Lens: Schneider F2.2/50mm
- Scintillation Screen: ZnS
- Zoom: 0.1375x



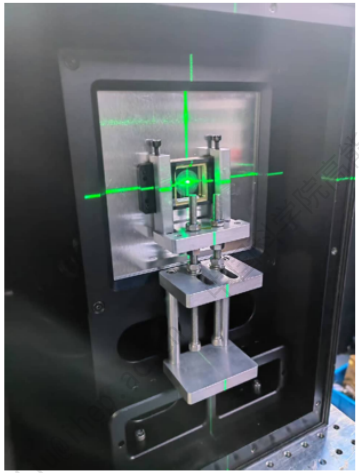


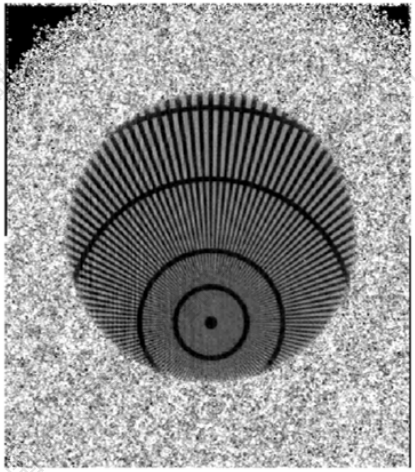
X-ray imaging by TPX4+300um Si

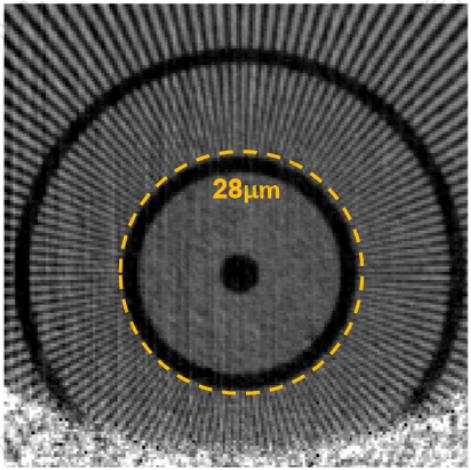
- FOV ≈ 100mm×100mm

验证性实验 - 能量分辨中子成像 - 空间分辨能力

- Sample: Siemens Star
- Lens: Schneider F4.5/85mm
- Scintillation Screen: GOS
- Zoom: x2.1



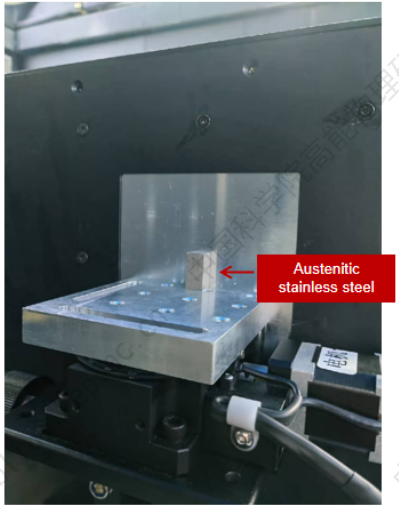


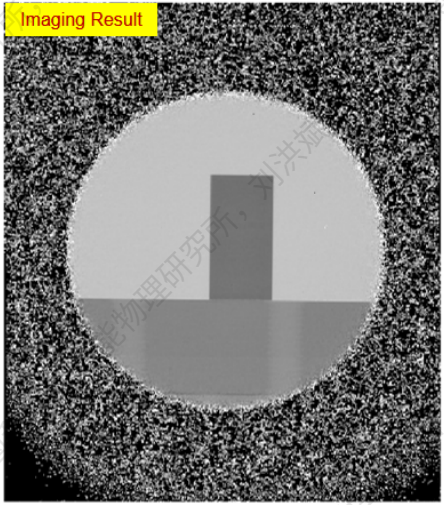


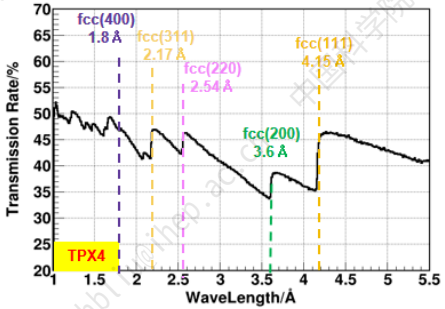
- FOV = Φ17mm/2.1 ≈ Φ8mm

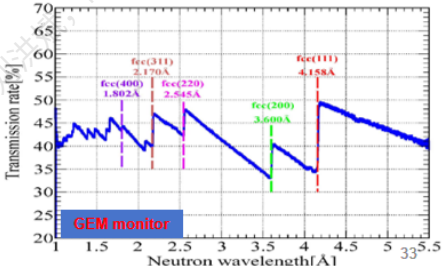
验证性实验 - 能量分辨中子成像 - 布拉格边成像

- Sample: Austenitic stainless steel
- Lens: Nikon F2.8/105mm
- Scintillation Screen: ZnS
- Zoom: 0.348x







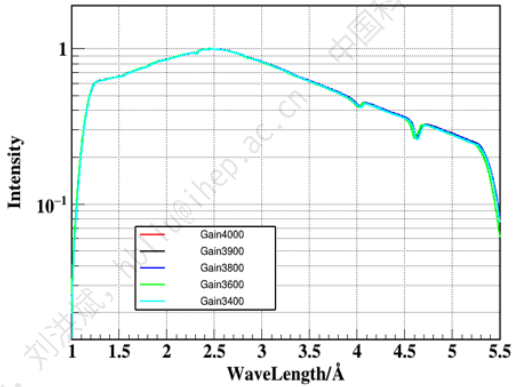


- **TPX4 Bragg-edge measurement of austenitic steel is consistent with GEM monitor**

验证性实验 - CSNS BL20直通束测试计数率能力

- Sample: n/a
- Lens: Schneider F2.8/105mm
- Scintillation Screen: ZnS
- Zoom: 0.348x

Data File	Img. Int. Gain	Duration	File Size	Data Rate	Average Counting Rate	Maximum Counting Rate
BL20_Raw data_Nikon105_C0_5_ZnS_OpenBeam5	Gain3400	5min	4169MB	13.9MB/s	0.9M hits/s	3.4M hits/s
BL20_Rawdata_Nikon105_C0_5_ZnS_OpenBeam4	Gain3600	5min	13903MB	46.3MB/s	2.89M hits/s	11.2M hits/s
BL20_Rawdata_Nikon105_C0_5_ZnS_OpenBeam3	Gain3800	5min	29525MB	98.4MB/s	6.1M hits/s	23.5M hits/s
BL20_Rawdata_Nikon105_C0_5_ZnS_OpenBeam2	Gain3900	5min	37853MB	126.2MB/s	7.8M hits/s	30.1M hits/s
BL20_Rawdata_Nikon105_C0_5_ZnS_OpenBeam1	Gain4000	5min	44168MB	**147.2MB/s**	9.2M hits/s	**35.5M hits/s**



- **Maximum event rate measured at CSNS BL20 was 35.5M hits/s**
- **TOF peak saturation was not observed**

目录

总结

- **Timepix4是一款由Medipix4合作组研制的复合式像素探测器读出芯片**
  - 55 um 像素间距，X,Y,TOA,TOA （200ps） 多维度事例信息测量，80Gbps/160Gbps bandwidth per chip
  - TSV + 铜柱 工艺已基本就绪
  - 工作模式：事例读出（极限2.5Gcps）/帧读出（最高80kfps@8bit）
- **IHEP-CSNS基于Timepix4研制了一套高速辐射成像系统**
  - 支持全带宽读出 （目前受限于互联结构，运行在80Gbps/芯片）
  - 峰值计数率能力1.2Gcps，长期可以运行在400Mcps计数率
  - 已经初步完成多种放射源、电子束、中子束流、X射线成像验证实验
- **下一步计划**
  - 帧读出，多芯片(1x4)拼接实现大探测面积，实时数据预处理
  - 不同传感层材料：CdTe，CZT, GaAs，钙钛矿
  - 应用研究：完善系统性能刻度，开展不同应用实验，解决真实的科学问题，TPC读出等
- **欢迎联系我们开展科学应用合作！**