



质子束流望远镜 进展报告

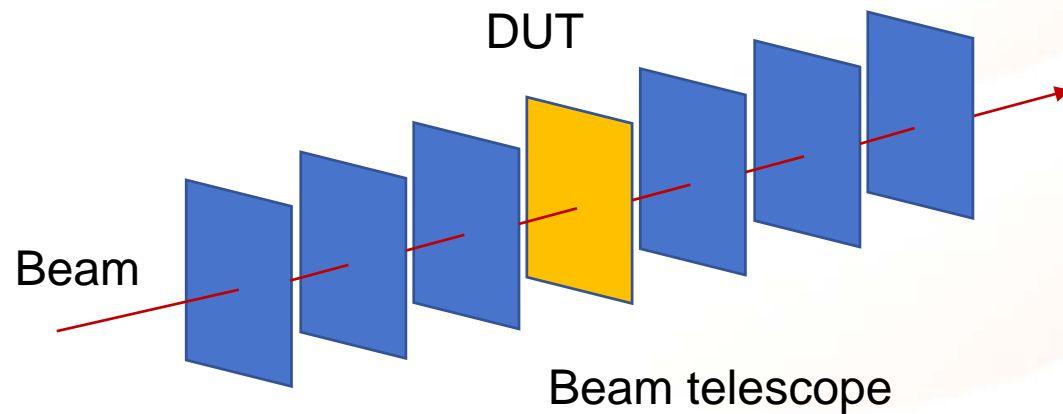
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Oct. 19. 2023



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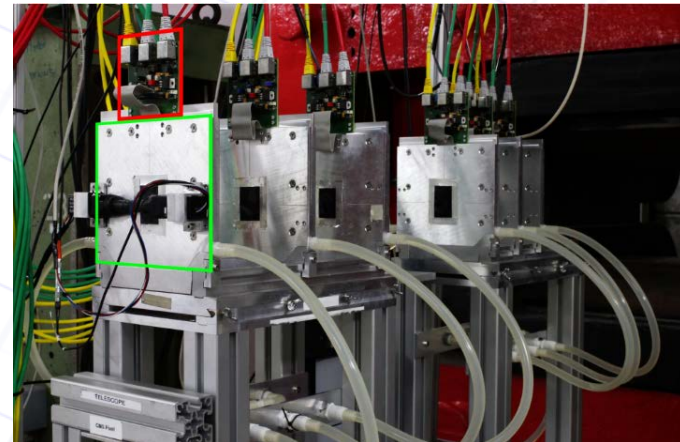
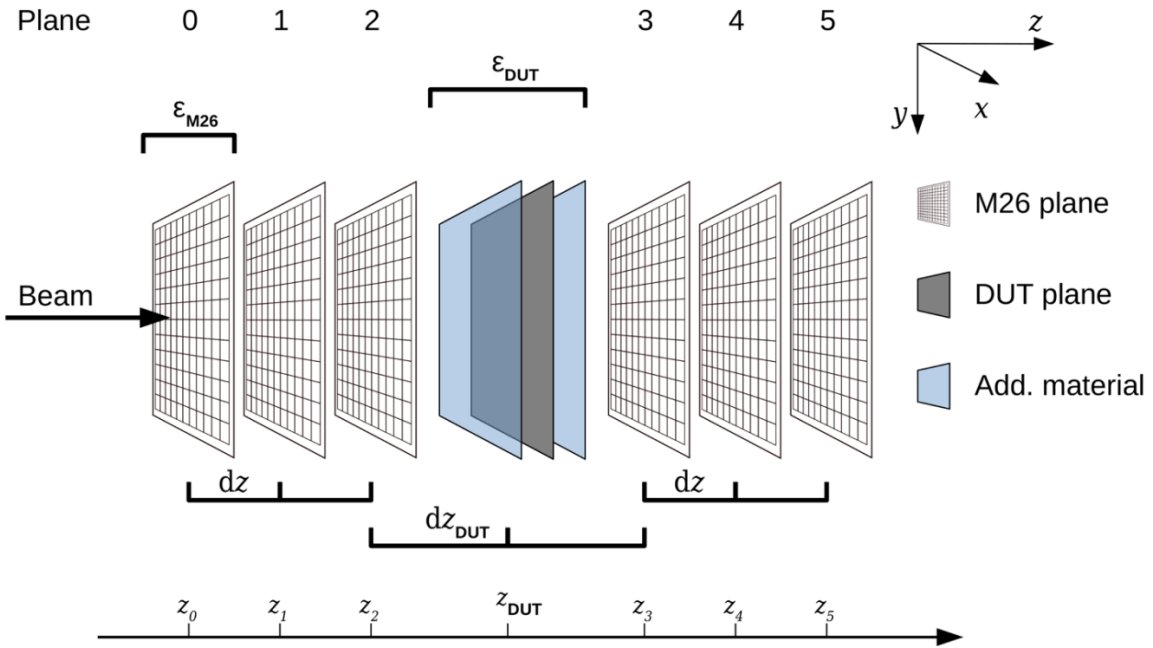




束流望远镜

- 束流实验中提供高精度的参考径迹的必要探测器
- 主要参数：
 - 位置分辨率
 - 灵敏区面积
 - 物质质量
 - 探测效率
 - 读出速度

主要参数	EUDET	CSNS质子束流望远镜
层数	6	6
像素尺寸 (μm^2)	18.4×18.4	~20×20
灵敏区面积 (mm^2)	21.2×10.6	>300
物质质量 ($\% X_0$)	0.07	0.053+0.035 50 μm silicon + <100 μm kapton
探测效率	99.5%	99.5%
径迹位置分辨率 (μm)	1.33@180GeV 1.83@6GeV 180 @50MeV	<10@1.6GeV
最大触发率	3.9kHz	~1kHz

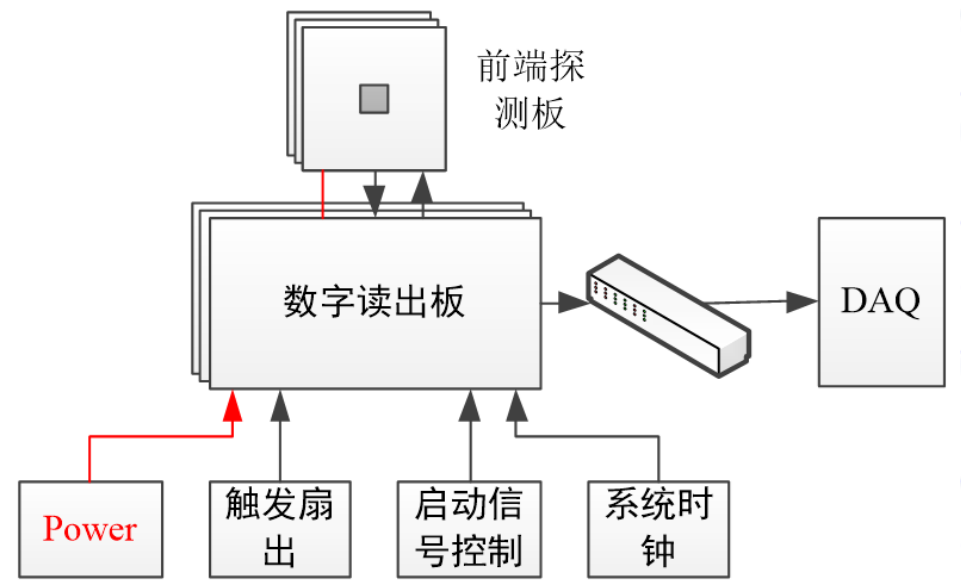
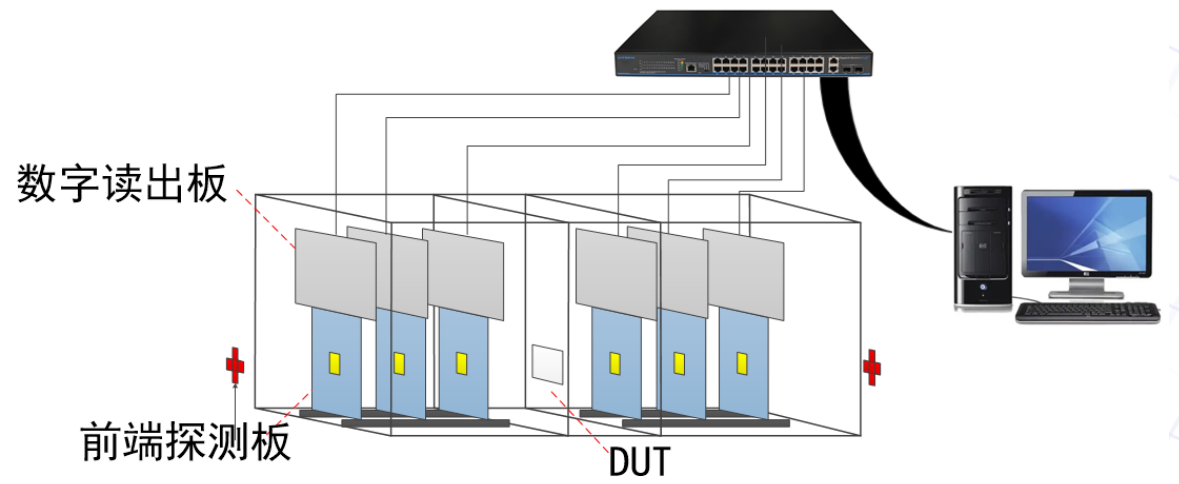
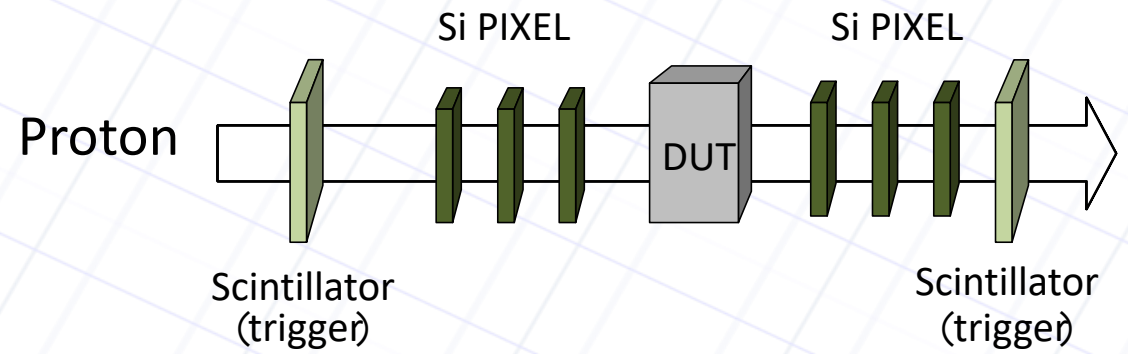




束流望远镜

束流望远镜结构组成:

- 6层探测模块: 包括硅像素探测器芯片, 前端探测板和数字读出板
- 电子学系统: 配置芯片, 提供电源和外部时钟, 数据打包与传输
- DAQ系统: 控制芯片工作和数据读取
- 触发系统: 提供触发信号
- 冷却系统和机械支撑系统等





模拟

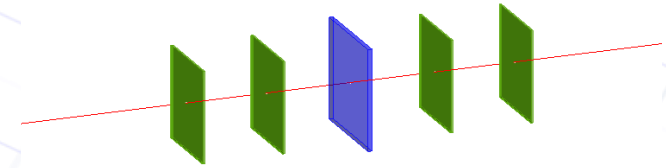
束流望远镜系统布局:

- 模拟能量: 1.6GeV质子
- 模型: 4层, 5层和6层望远镜+1层DUT, 每层物质质量0.088% X_0
- 望远镜layout: 减小望远镜间距以提高测量精度
- 望远镜层数: 1.6GeV时6层望远镜增大大多次库仑散射的影响, 4层望远镜测量精度略好
- 望远镜分辨率~2.2 μm

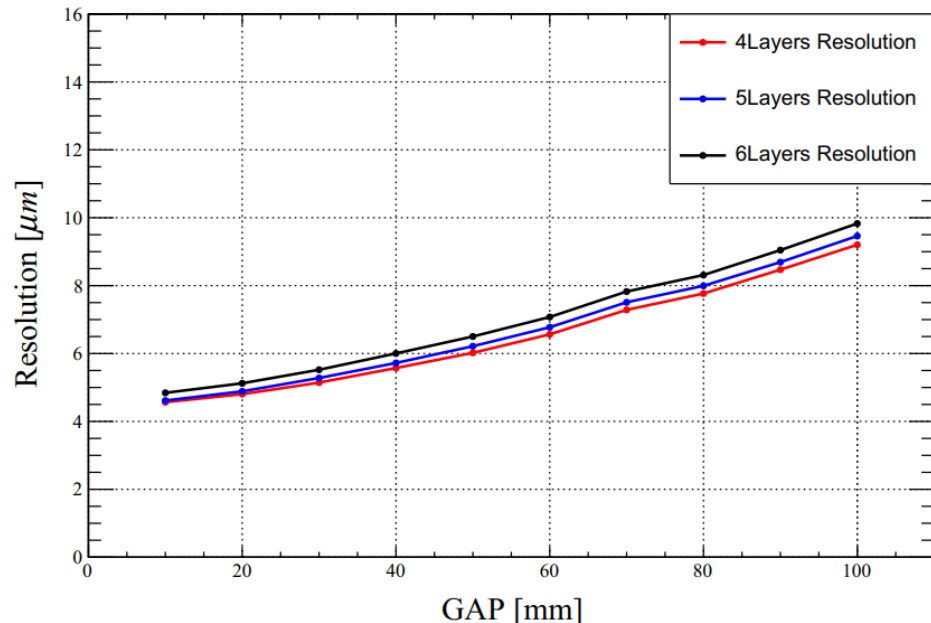
$$\text{测量空间分辨率: } \sigma_{\text{meas}}^2 = \sigma_{\text{DUT}}^2 + \sigma_{\text{tel}}^2$$

$$\sigma_{\text{tel}}^2 = k\sigma_{\text{DUT}}^2$$

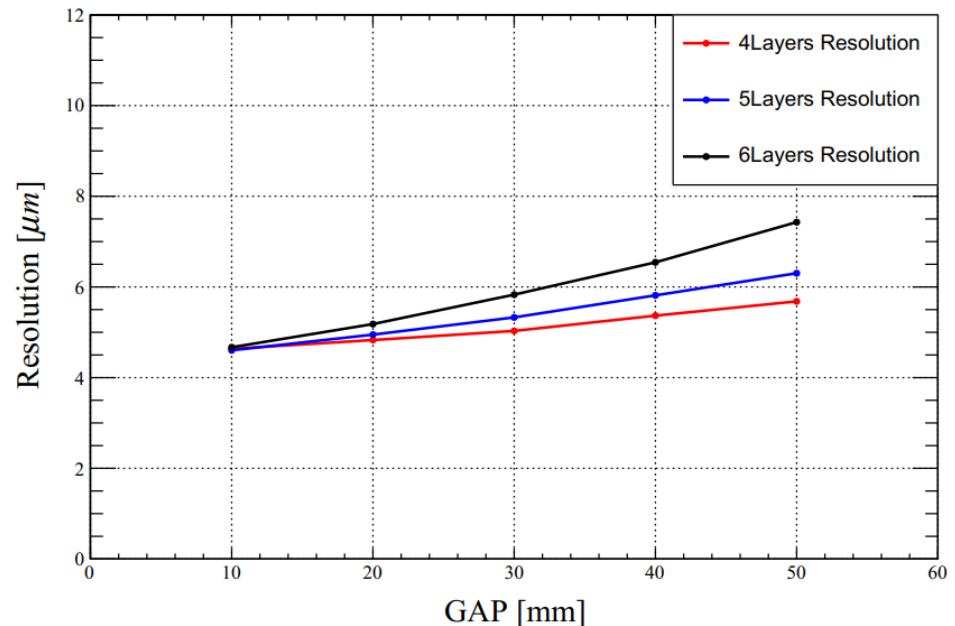
$$k = \frac{\sum_i^N z_i^2}{N \sum_i^N z_i^2 - \left(\sum_i^N z_i\right)^2}$$



Resolution VS DUT GAP



Resolution VS Telescope GAP



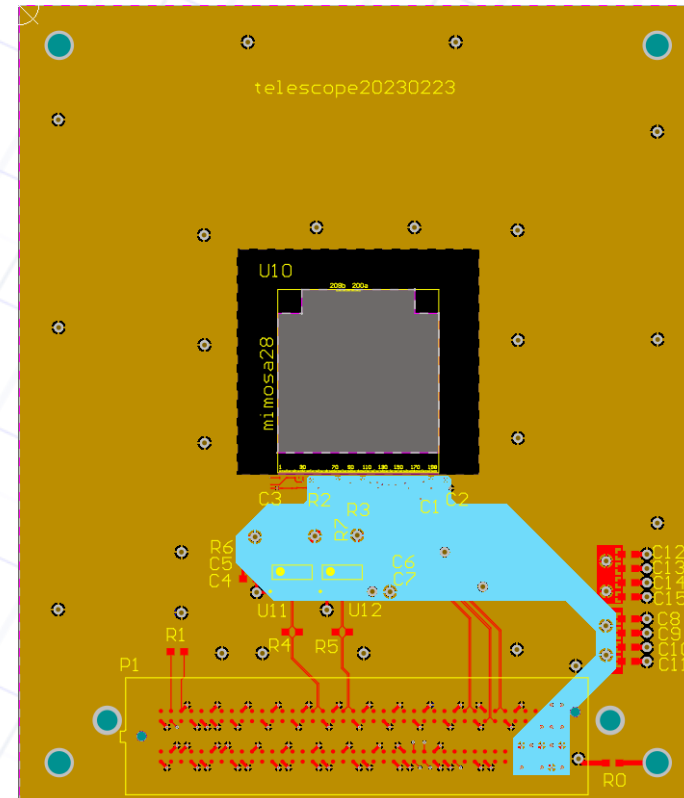
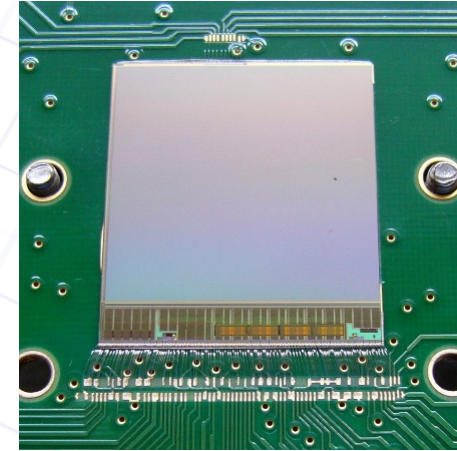


探测模块

- 探测模块的前端芯片板通过wire-bonding与芯片连接
- 通过两角和打线部分留出的粘贴位置，在保证芯片粘贴足够稳固的前提下，其余灵敏区位置开槽
- 低质量的灵敏区面积~ 3.6cm^2

MIMOSA28探测模块参数

- 像素尺寸: $20.7\mu\text{m}$
- 灵敏区: $928*960$, $\sim 3.8\text{cm}^2$
- 空间分辨率: $\sim 4\mu\text{m}$
- 功耗: $150\text{mV}/\text{cm}^2$
- 读出时间: $185.6\mu\text{s}$
- 厚度/物质质量: $50\mu\text{m}/0.053\%X_0$

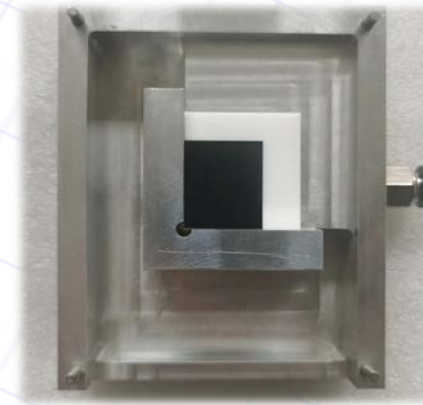




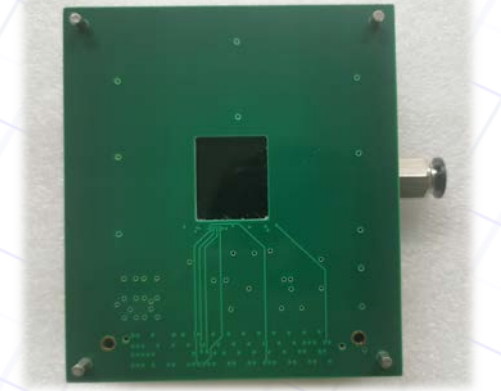
模块研制

高精度贴片及打线

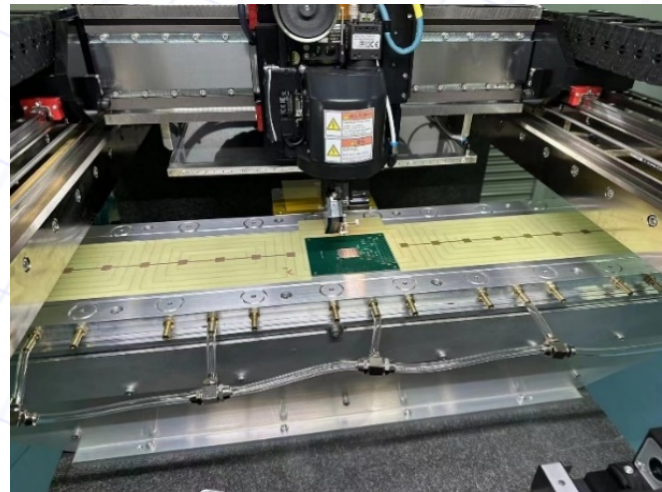
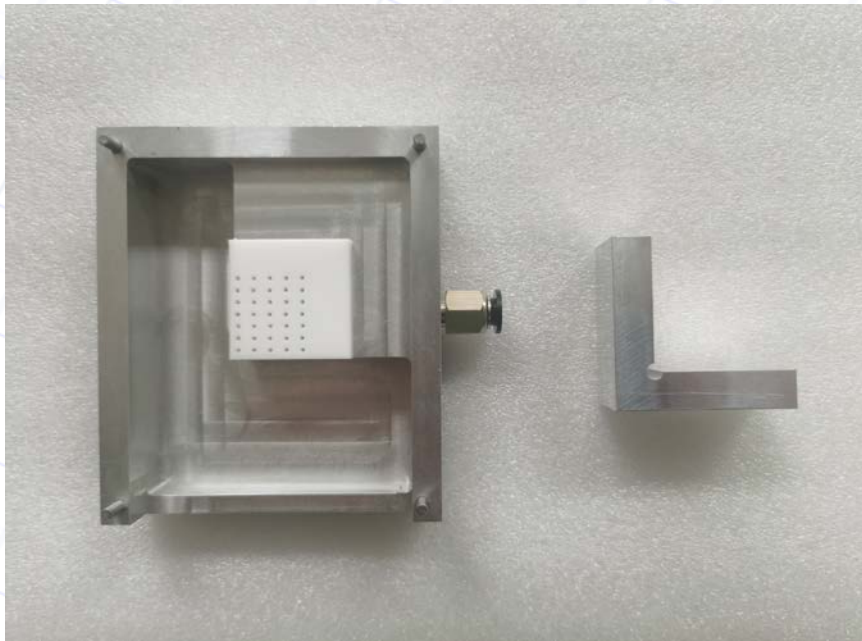
- 通过L型定位面精确摆放芯片
- 打开抽气系统，移走L型定位面
- 通过定位销和PCB板上的定位孔精确放置前端芯片板
- 探测模块均匀受压以充分粘接
- 使用Hesse BJ855全自动引线键合机完成打线



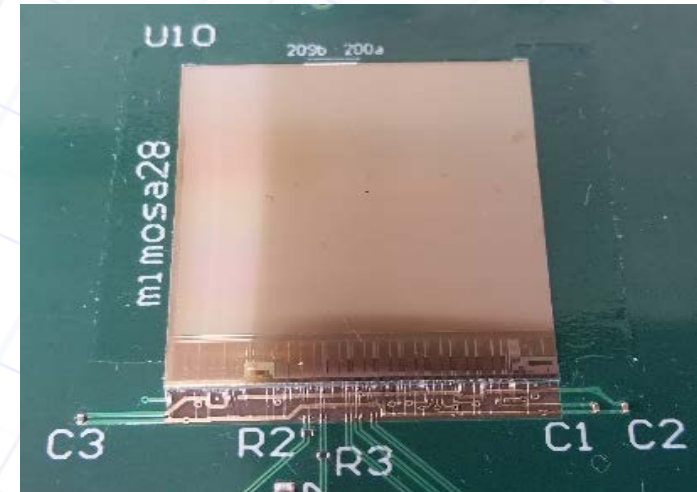
(a) 芯片放置



(b) 前端板放置



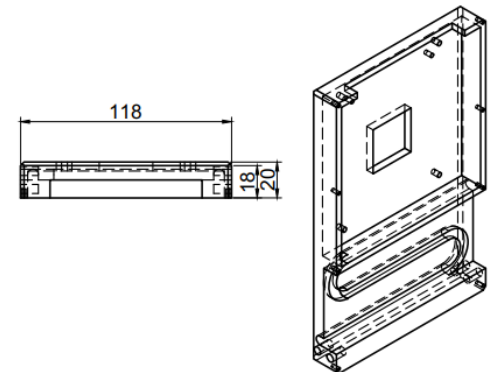
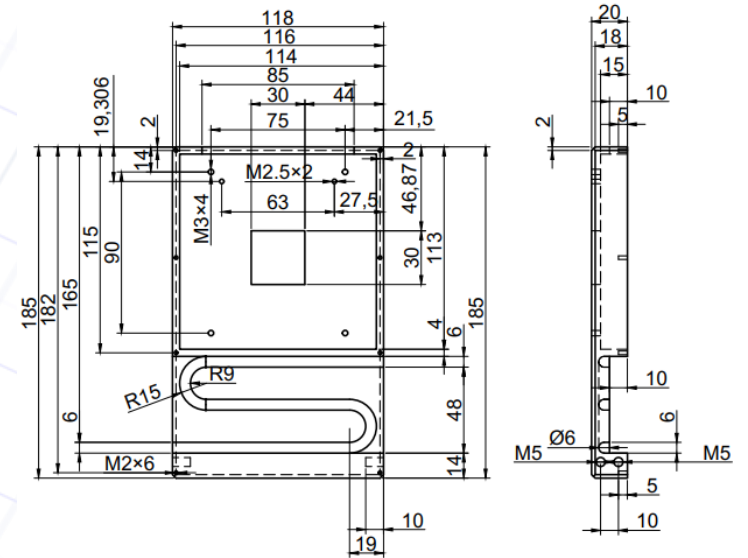
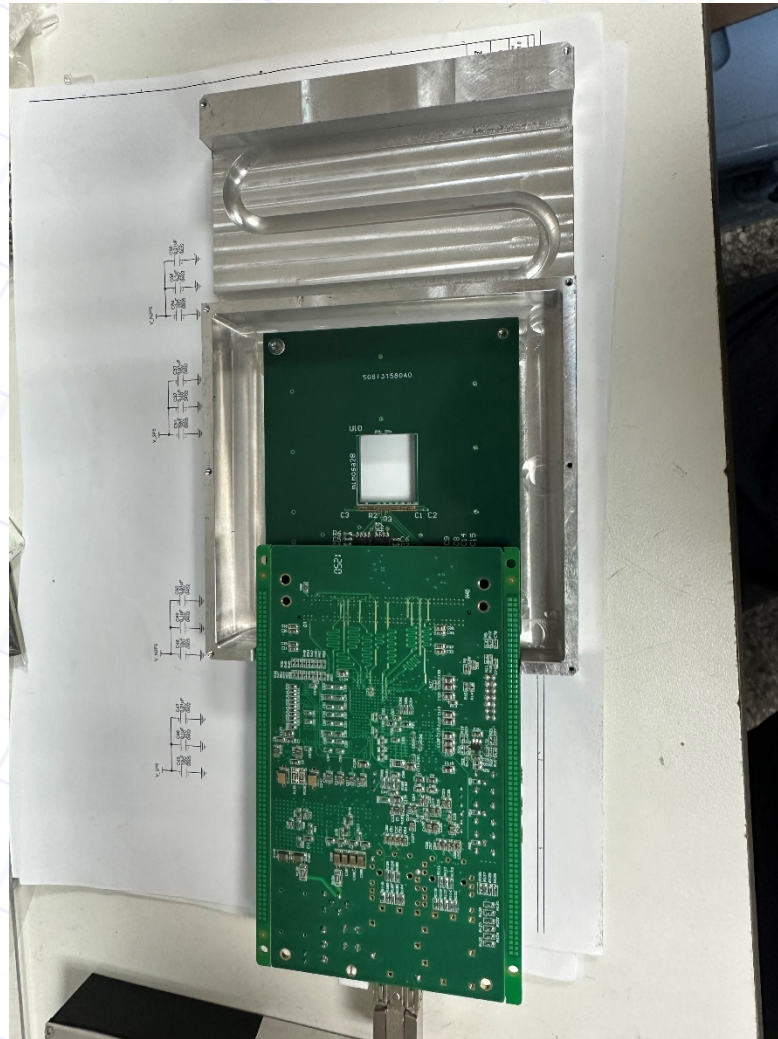
(c) 芯片打线 (BJ855键合机, 25 μm 铝丝)





探测模块支撑盒

- 支撑前端板和读出板
- 芯片避光
- 散热，通过水冷降低壳体温度
- 将读出板大部分放在壳体外侧，减少壳体内部温度
- 优化尺寸，减轻重量



电子学系统包括:

- 前端芯片板, 通过wire-bonding连接芯片, 并通过JTAG接口连接到数字读出板
- 数字读出板, 用于配置芯片, 提供电源和外部时钟, 数据打包并传输等
- 时钟扇出板, 提供100MHz外部时钟, 同步多个芯片工作状态
- 触发扇出板, 接收触发信号, 并在数字读出板中打包
- Start控制板和扇出板



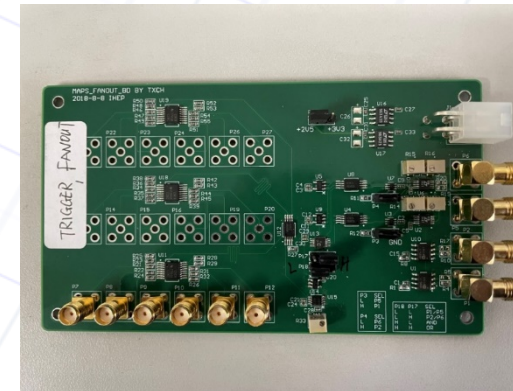
前端芯片板



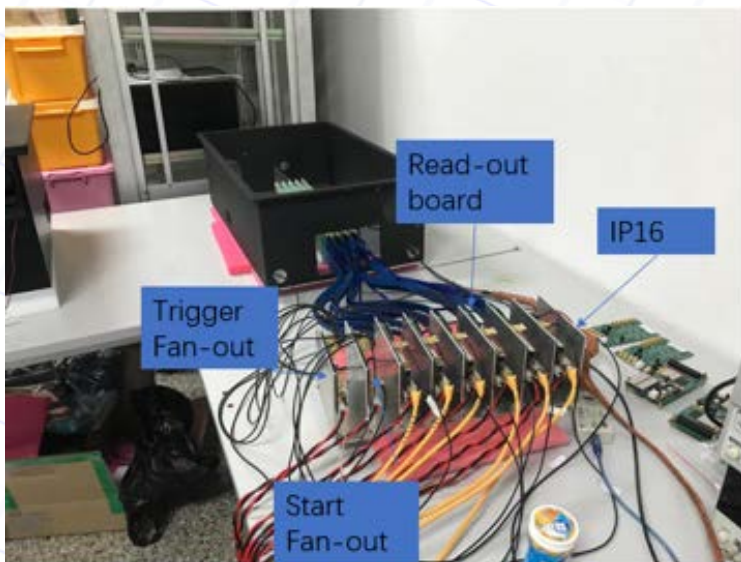
数字读出板



时钟扇出板



触发扇出板





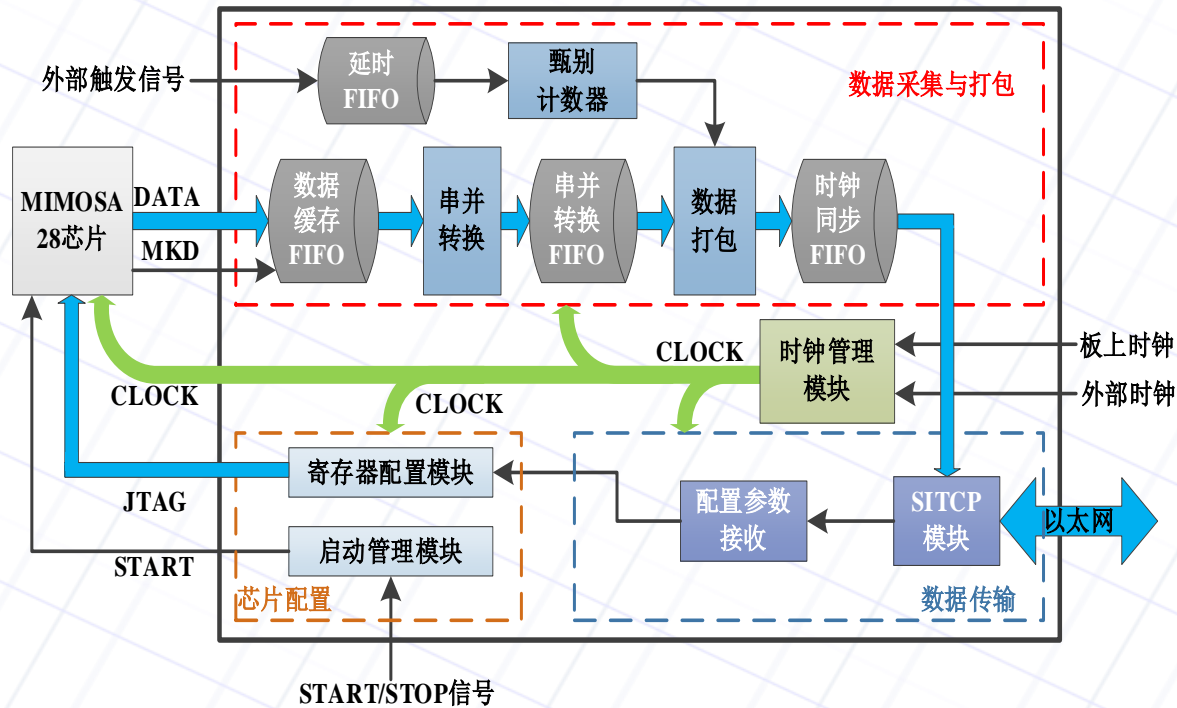
读出电子学

FPGA固件主要功能:

- ❑ 与工控机的传输, 芯片寄存器配置
- ❑ 数据缓存及串并转换
- ❑ 接受外部触发信号, 并加入数据包中
- ❑ 接受外部时钟信号, 保证多模块同步工作

连续读出方式:

➤ 连续读出+触发标记 → 不会丢包, 死时间为0, 在前后三帧数据匹配击中事例



Package Header: 0XCCCC01
Package Trigger Count: 32 bit
Package Frame Count: 32 bit
Package Data Length: 32 bit
Chip Header: 0X33333331
Header: 0X12345678
Chip Frame Count: 32 bit
Chip Data Length: 32 bit
RAW Data
⋮
Chip Trailer: 0Xaaaaaaaa
Package Trailer: 0X99999999
Package Header: 0XCCCC01
⋮

数据格式

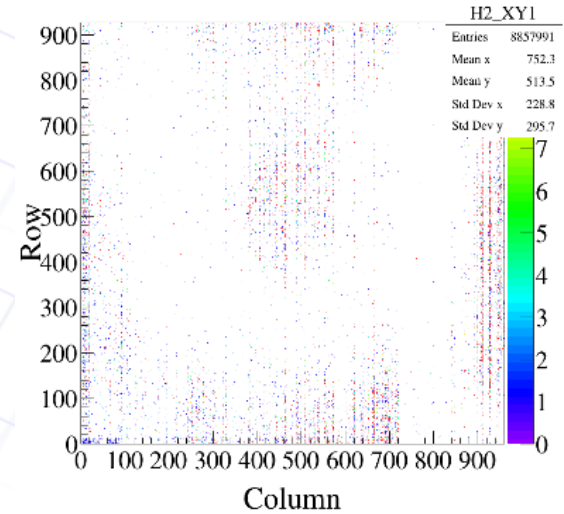


噪声测试

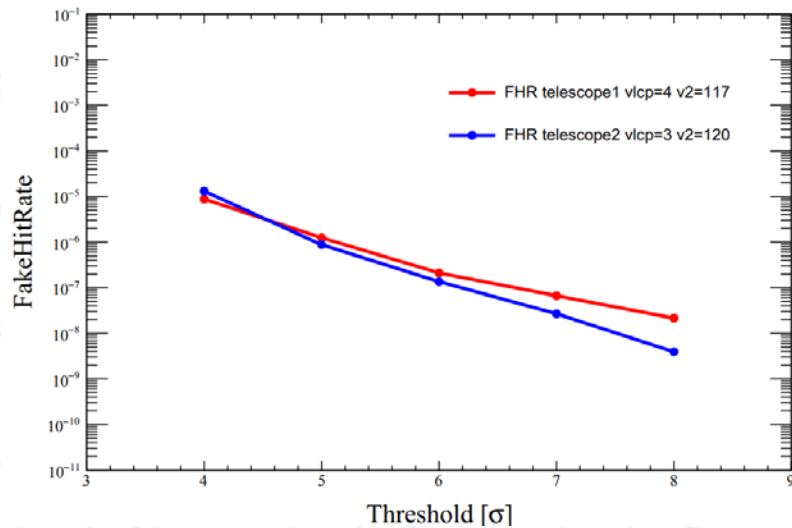
- 不加放射源和外部输入时，连续取数20w帧，研究不同阈值下的噪声水平
- 定义FakeHitRate为

$$FHR = \frac{\text{All fired pixels}}{\text{Pixels} \times \text{All frame}}$$

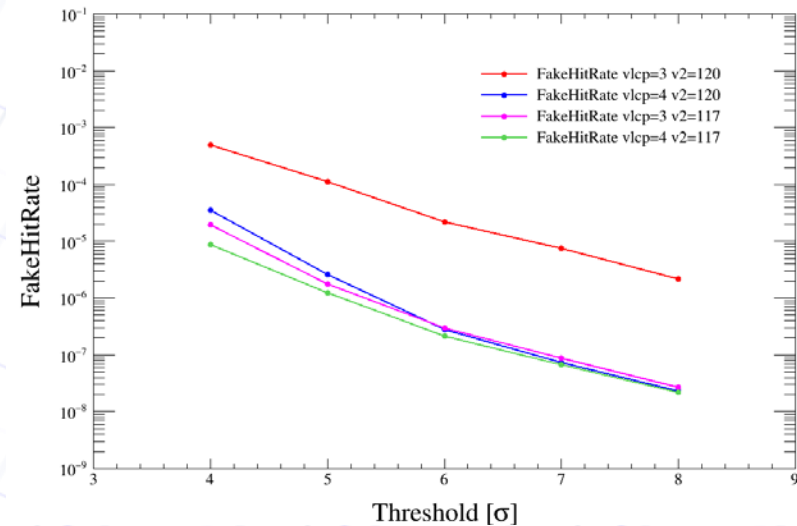
- 减少噪声：1.提高钳位电压VCLP。2.减小全局阈值V2→有效降低固态模式噪声
- 阈值 $>5\sigma$ 时，FakeHitRate $<10^{-6}$ ，即每帧不超过一个着火像素



FakeHitRate VS Threshold



FakeHitRate VS Threshold

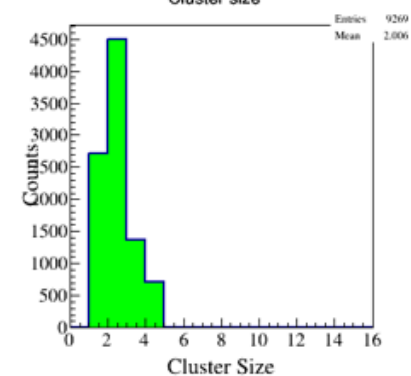
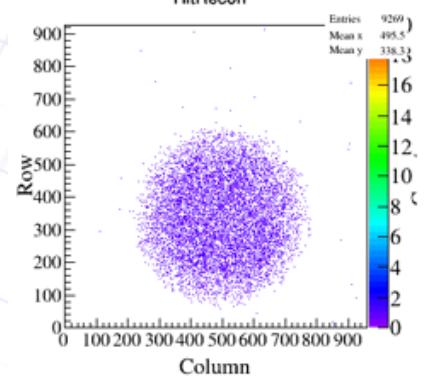
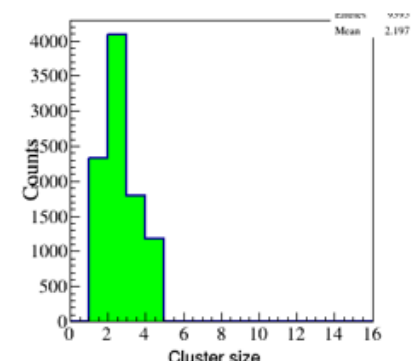
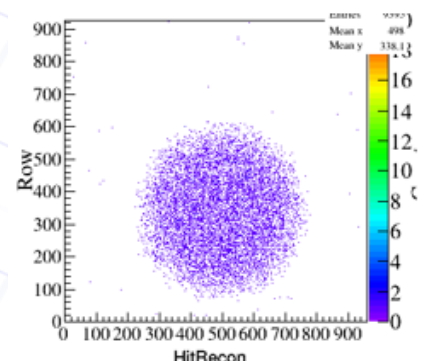
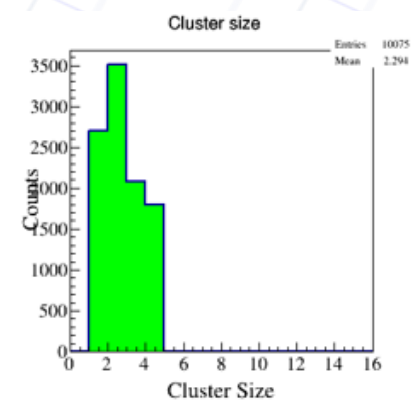
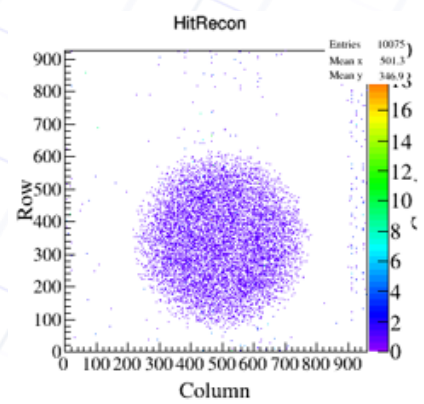
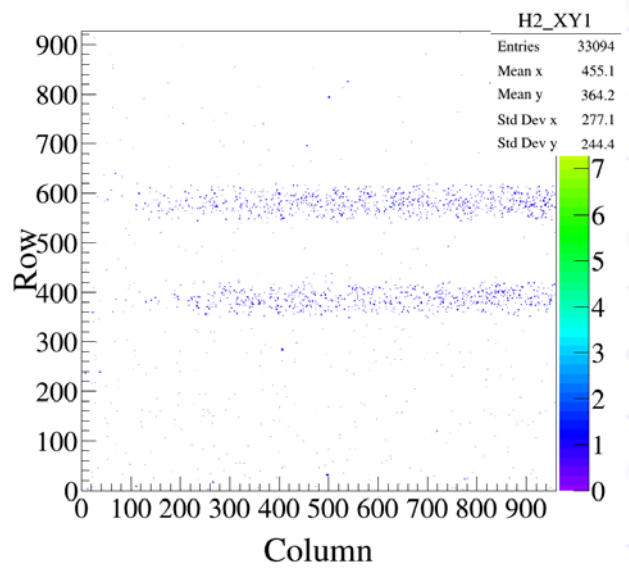
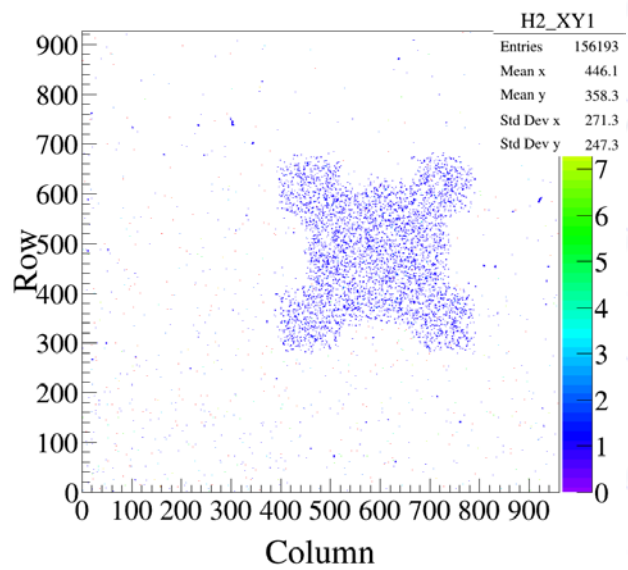


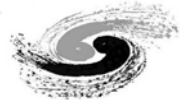


放射源测试

^{55}Fe 放射源响应:

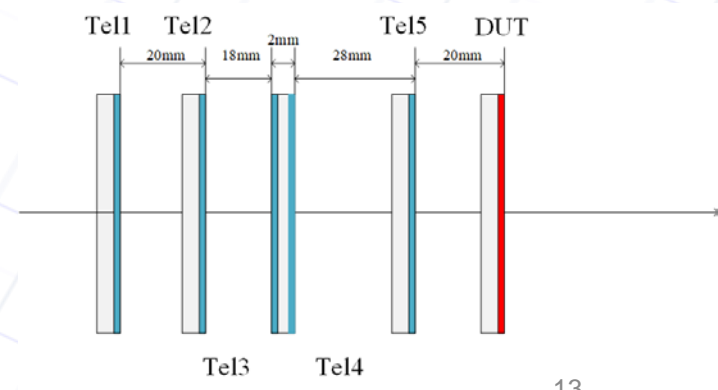
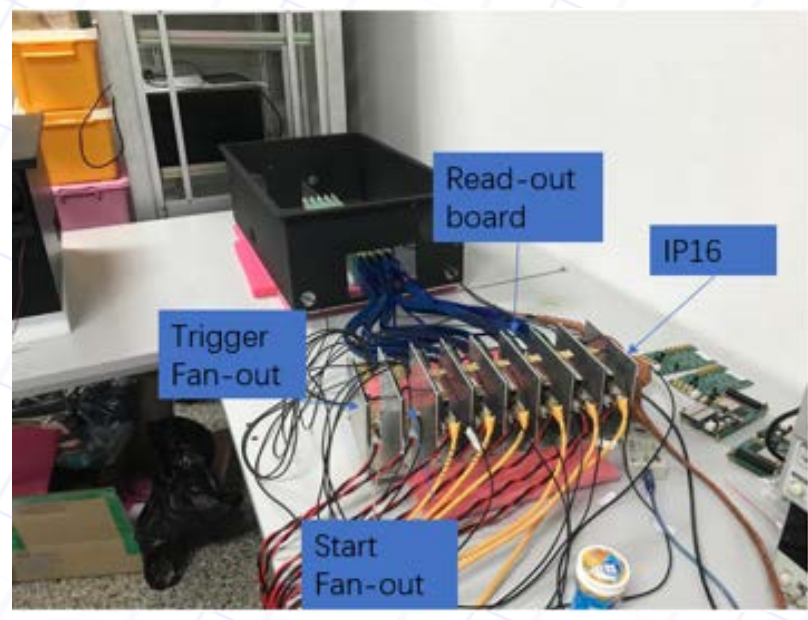
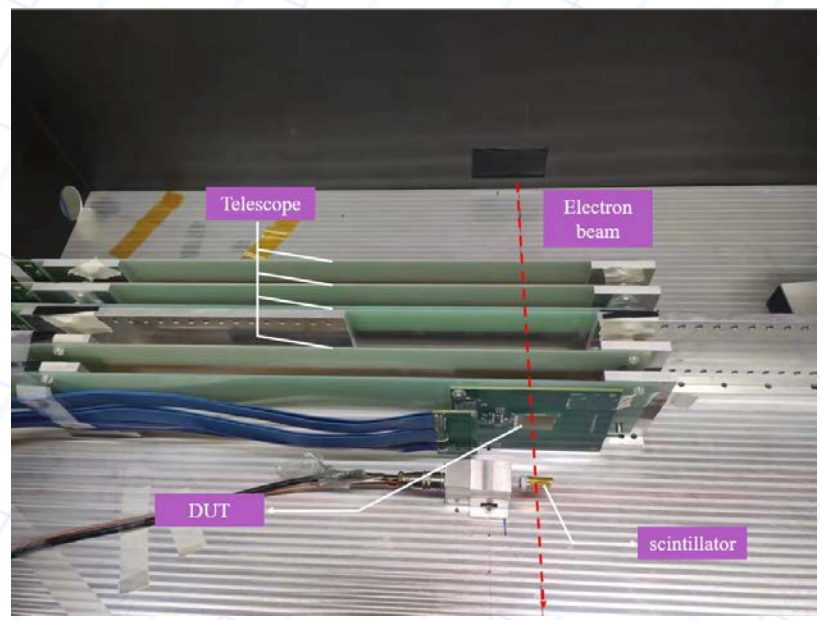
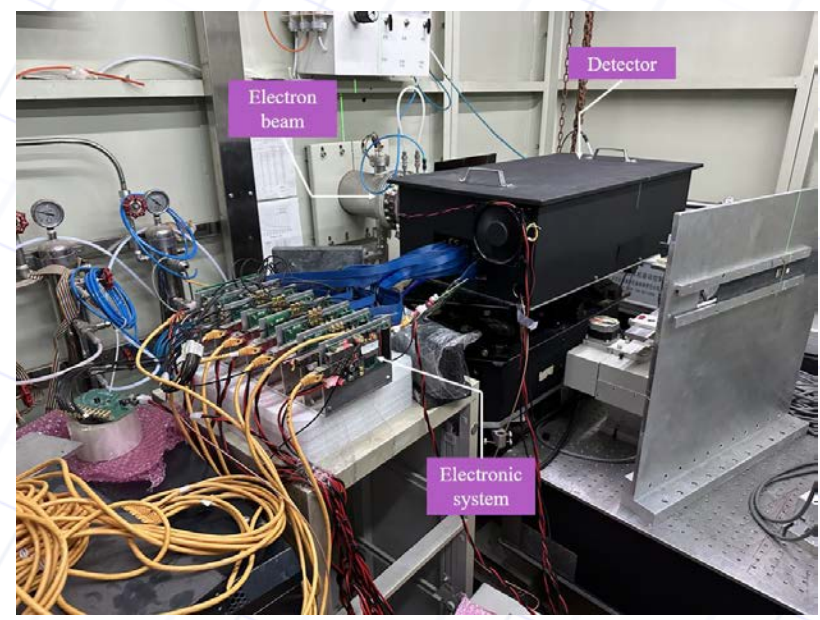
- 使用不同的模具，验证了探测模块对放射源的响应无误
- 改变阈值，簇团大小随阈值增大而减小





初步束流测试

- 束流：同步辐射线站，光子中存在部分电子
- 能量：经过铅皮散射后~1.3GeV，能散较大
- 六层探测模块组成探测器系统
 - 望远镜系统（5层）+ 待测模块（DUT）位于最外层，且绕z轴旋转90°（受限于本次测量的支撑结构）
 - 闪烁体：提供触发信号



离线分析

□ 散射角分布

- Tel2+Tel3 → 径迹的入射角
- Tel4+Tel5 → 径迹的出射角
- 散射角分布 ~ 1mrad

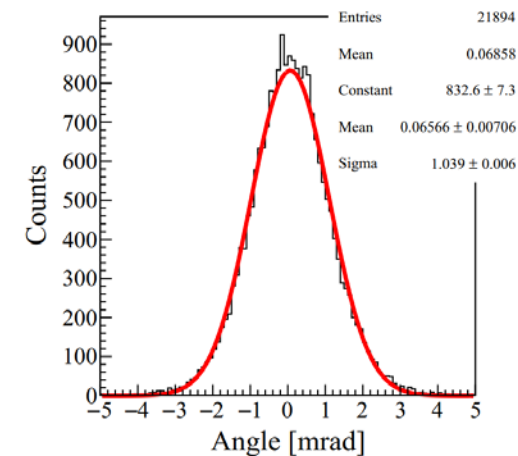
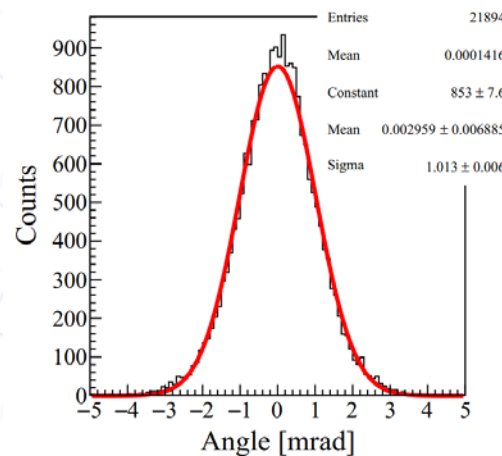
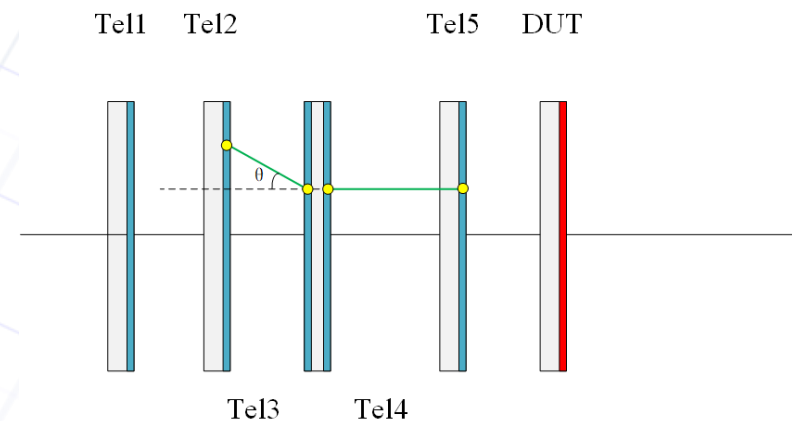


- 由物质质量0.48% $X_0 \rightarrow \theta_0 = 0.578\text{mrad}$, 小于实际的散射角分布, 可以判断存在低能电子

- 筛选径迹: 排除散射角大于 $2\theta_0$ 的低能电子

- Highland公式

$$\theta_0 = \frac{13.6\text{MeV}}{\beta c p} Z \sqrt{\frac{x}{X_0}} (1 + 0.038 \ln(\frac{x}{X_0}))$$

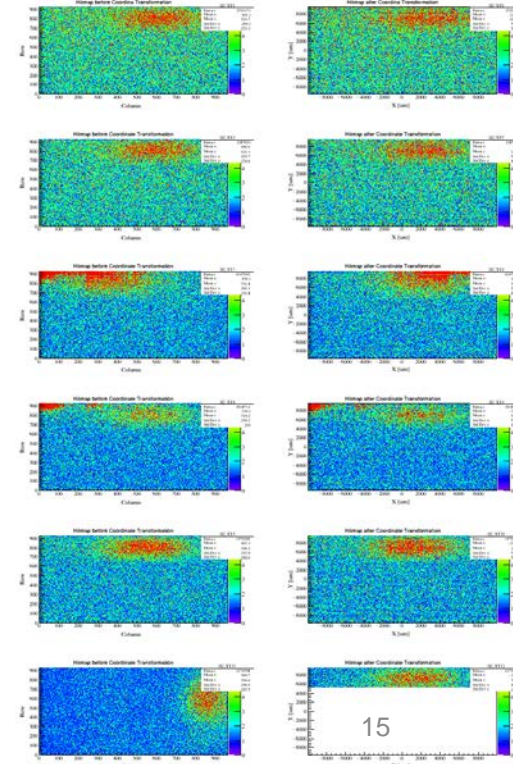
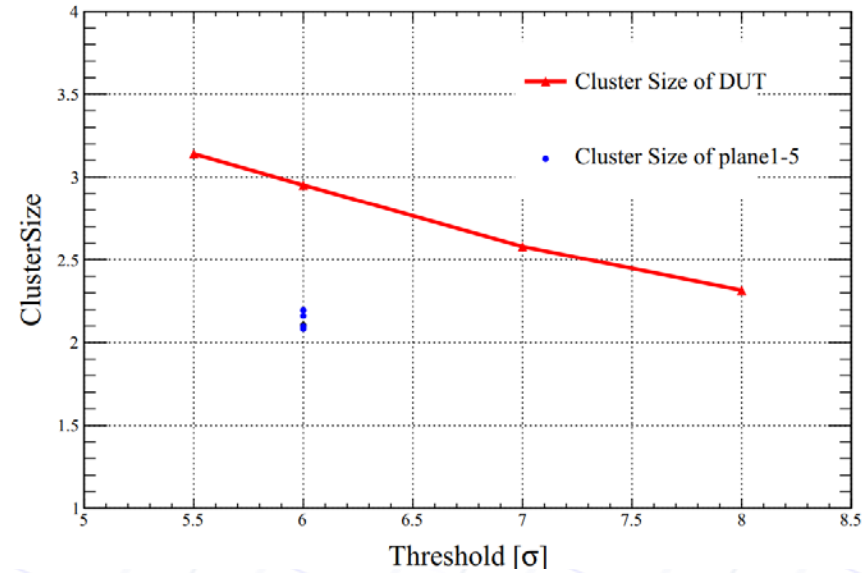
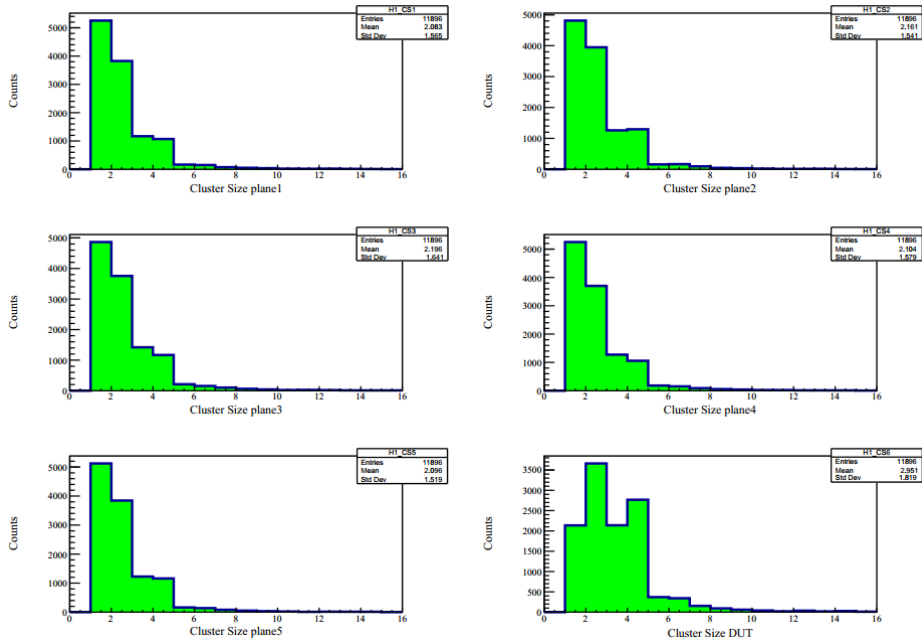
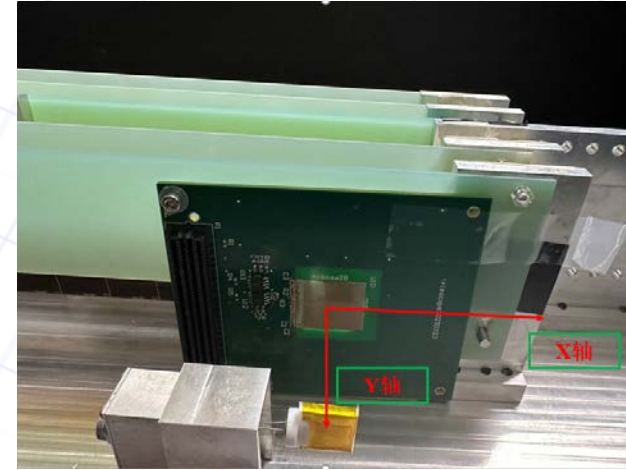




束流实验

簇团重建及坐标转换:

- Tel3和Tel4是double-sided ladder正反两层，Tel3与Tel4镜像对称
- DUT与前五层望远镜只有部分重合
- DUT绕x轴旋转 $\sim 5^\circ$ \rightarrow 增大灵敏区厚度 \rightarrow 相同阈值(6 σ)下cluster size增大40%





束流实验

校准:

➤ 同一粒子产生的击中坐标存在位置相关性→相邻两层击中坐标残差分布均值作为XY方向初始偏移

➤ 校准参数M:

$$M = (\Delta u, \Delta v, \Delta w, \Delta\alpha, \Delta\beta, \Delta\gamma)$$

➤ 校准前局部坐标系到校准后全局坐标系→测量残差和校准参数的关系:

- 测量残差

$$r_j = J_j^T M^T \quad r_j = \begin{pmatrix} u_j^c - u_j \\ v_j^c - v_j \end{pmatrix}$$

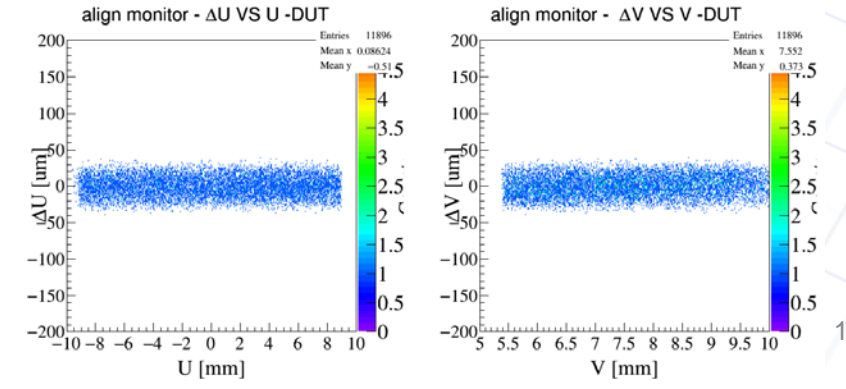
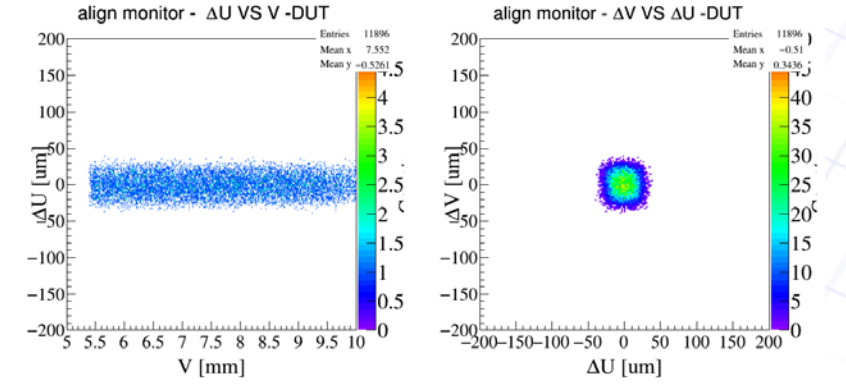
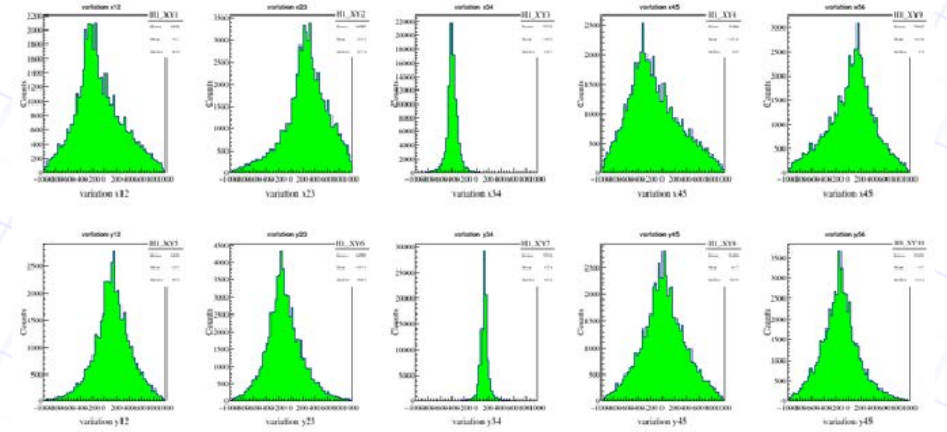
- 雅可比矩阵

$$J_j^T = \begin{pmatrix} -1 & 0 & \tan\phi & v_j \tan\phi & u_j \tan\phi & v_j \\ 0 & -1 & \tan\psi & v_j \tan\psi & u_j \tan\psi & -u_j \end{pmatrix}$$

➤ 构造函数和线性回归计算校准参数M

$$M^T = (JJ^T)^{-1} J r = \sum_j J_j J_j^T \sum_j J_j r_j$$

➤ 校准精度好于0.2μm





束流实验

径迹拟合:

- Kalman滤波径迹拟合+协方差矩阵引入多次库伦散射
- 最小二乘法寻迹, 获得径迹初始参数(x_0, y_0 和斜率)
- 预测: 根据状态传递模型 F_k 预测径迹参数和协方差矩阵

$$\hat{x}_k^{k-1} = F_{k-1}\hat{x}_{k-1}$$

$$C_k^{k-1} = F_{k-1}C_{k-1}F_{k-1}^T + Q_{k-1}$$

- 计算Kalman增益: 根据测量模型 H_k 和协方差矩阵计算Kalman增益

$$K_k = C_k^{k-1}H_k^T (H_kC_k^{k-1}H_k^T + U_k)^{-1}$$

- 更新: 根据测量值和预测值的残差更新径迹参数及协方差矩阵

$$\hat{x}_k^k = \hat{x}_k^{k-1} + K_k (m_k - H_k\hat{x}_k^{k-1})$$

$$C_k^k = (I - K_kH_k)C_k^{k-1}$$

径迹参数:

$$\hat{x} = \begin{pmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{pmatrix} = \begin{pmatrix} x_0 + z_0 \tan \theta_x \\ y_0 + z_0 \tan \theta_y \\ \tan \theta_x \\ \tan \theta_y \end{pmatrix}$$

状态传递模型

$$\hat{x}_k = F_{k-1}\hat{x}_{k-1} + w_{k-1}$$

$$= \begin{pmatrix} 1 & 0 & dz & 0 \\ 0 & 1 & 0 & dz \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ dx \\ dy \end{pmatrix} + Q_k$$

测量模型:

$$\hat{m}_k = H_k\hat{x}_k + \epsilon_k$$

$$= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ dx \\ dy \end{pmatrix} + V_k$$

传递过程中噪声的协方差矩阵 Q_k :

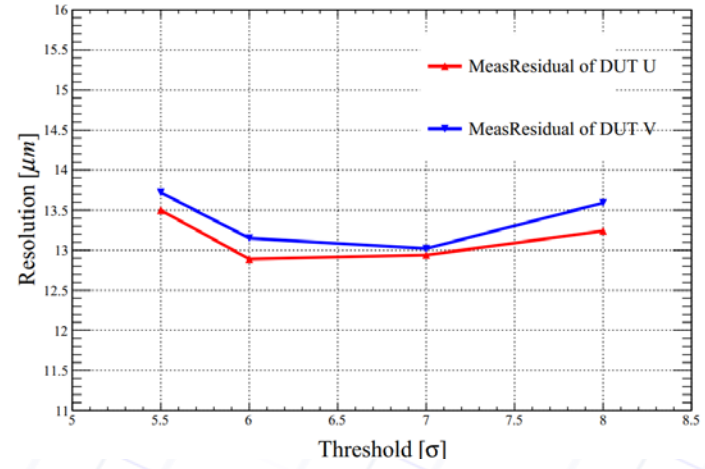
$$Q_k = \begin{pmatrix} z_0^2 \langle P_3, P_3 \rangle & z_0^2 \langle P_3, P_4 \rangle & z_0 \langle P_3, P_3 \rangle & z_0 \langle P_3, P_4 \rangle \\ z_0^2 \langle P_3, P_4 \rangle & z_0^2 \langle P_4, P_4 \rangle & z_0 \langle P_3, P_4 \rangle & z_0 \langle P_4, P_4 \rangle \\ z_0 \langle P_3, P_3 \rangle & z_0 \langle P_3, P_4 \rangle & \langle P_3, P_3 \rangle & \langle P_3, P_4 \rangle \\ z_0 \langle P_3, P_4 \rangle & -z_0 \langle P_4, P_4 \rangle & \langle P_3, P_4 \rangle & \langle P_4, P_4 \rangle \end{pmatrix}$$

$$\begin{aligned} \langle P_3, P_3 \rangle &= \sigma^2(\theta) (1 + P_3^2 + P_4^2) (1 + P_3^2) \\ \langle P_3, P_4 \rangle &= \sigma^2(\theta) (1 + P_3^2 + P_4^2) (P_3P_4) \\ \langle P_4, P_4 \rangle &= \sigma^2(\theta) (1 + P_3^2 + P_4^2) (1 + P_4^2) \end{aligned}$$



束流实验

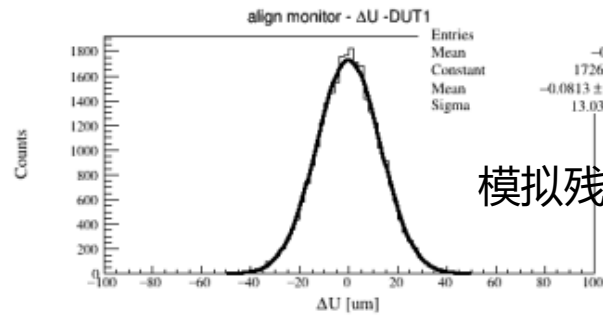
- 空间分辨初步分析结果: 12.89 μm (束流能量低、能散大, DUT放在最后一层), 此结果与模拟结果一致
- DUT放置在最后一层, $k \sim 1.37$, 而DUT放置在中间时 $k \sim 0.25$
- DUT放在中间时(此处将有支撑结构的ladde作为DUT), 空间分辨: 7.7 μm , 探测效率 > 99.5%
- 若将望远镜模块作为DUT放在中间+更好的束流条件将可获得更好的空间分辨
- 测试结果初步验证了系统的性能



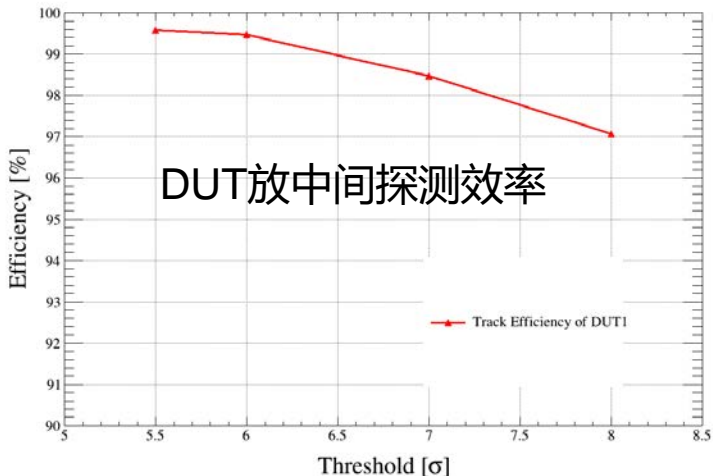
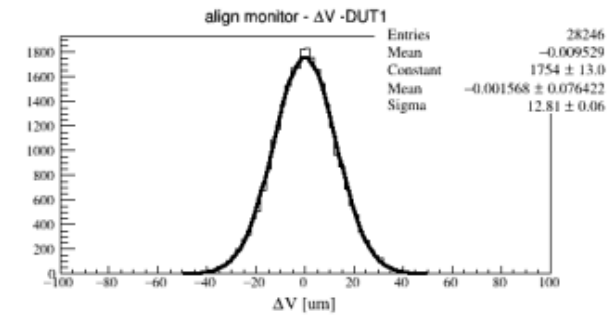
$$\sigma_{\text{meas}}^2 = \sigma_{\text{DUT}}^2 + \sigma_{\text{tel}}^2$$

$$\sigma_{\text{tel}}^2 = k \sigma_{\text{DUT}}^2$$

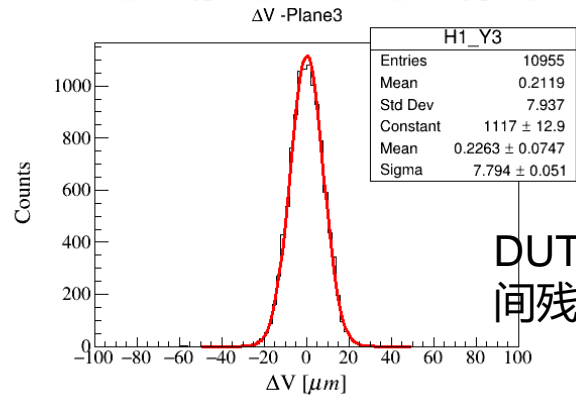
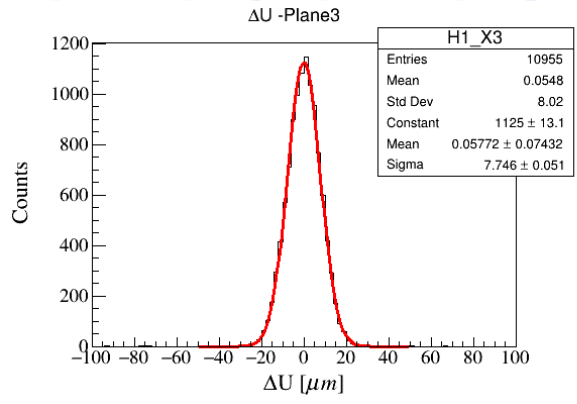
$$k = \frac{\sum_i^N z_i^2}{N \sum_i^N z_i^2 - \left(\sum_i^N z_i\right)^2}$$



模拟残差分布



DUT放中间探测效率



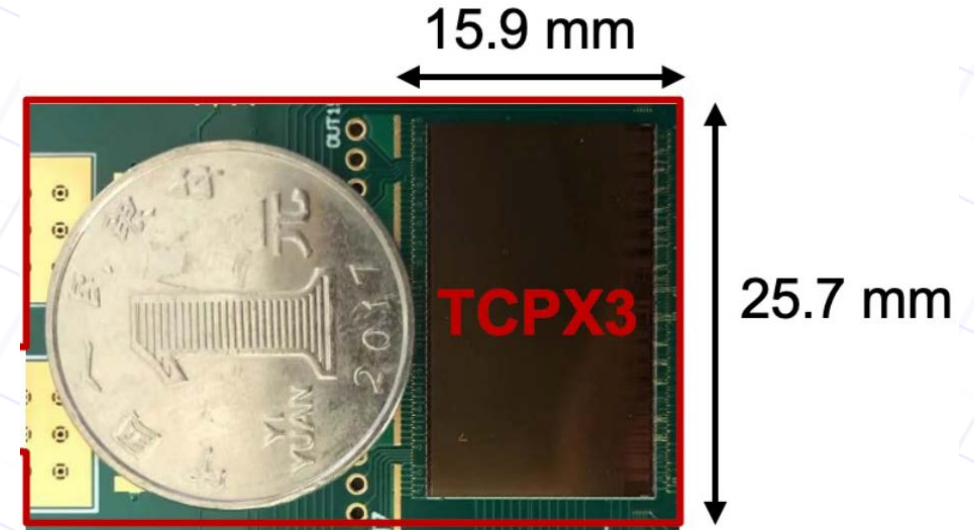
DUT放在中间残差分布



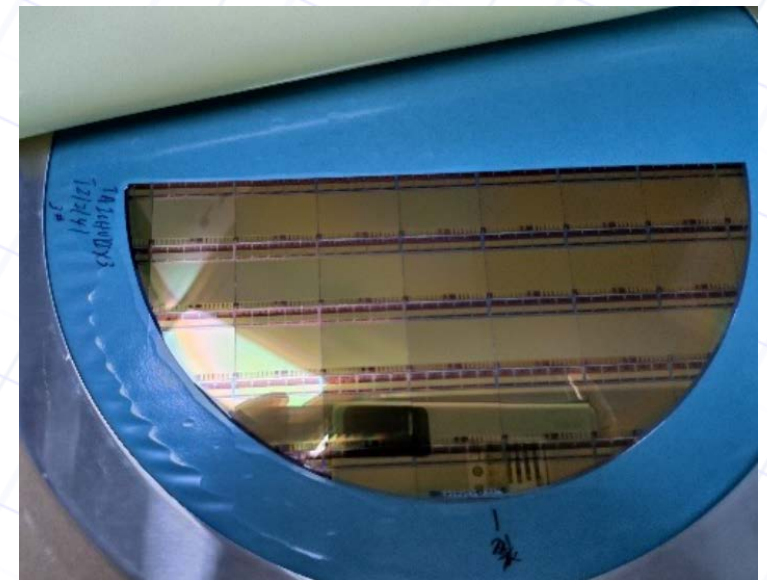
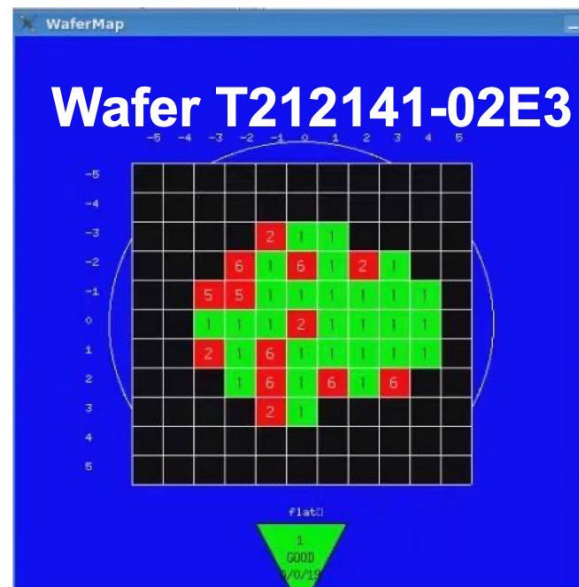
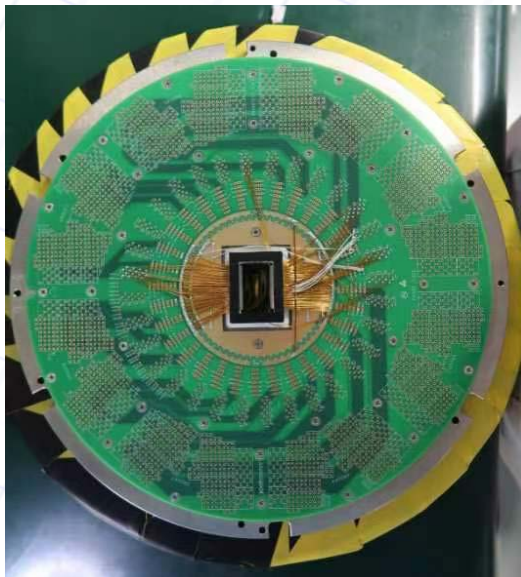
TaichuPix

自主研发，经过三次流片实现了全功能全尺寸太初芯片

- CEPC首个全尺寸、全功能的像素探测器芯片
- 1024×512 像素，芯片尺寸：15.9×25.7mm²
- 25 μm×25 μm 像素尺寸
- 工艺：Towerjazz 180nm CIS process
- 晶圆级探针卡测试也验证了成品率



TaichuPix-3 chip vs. coin

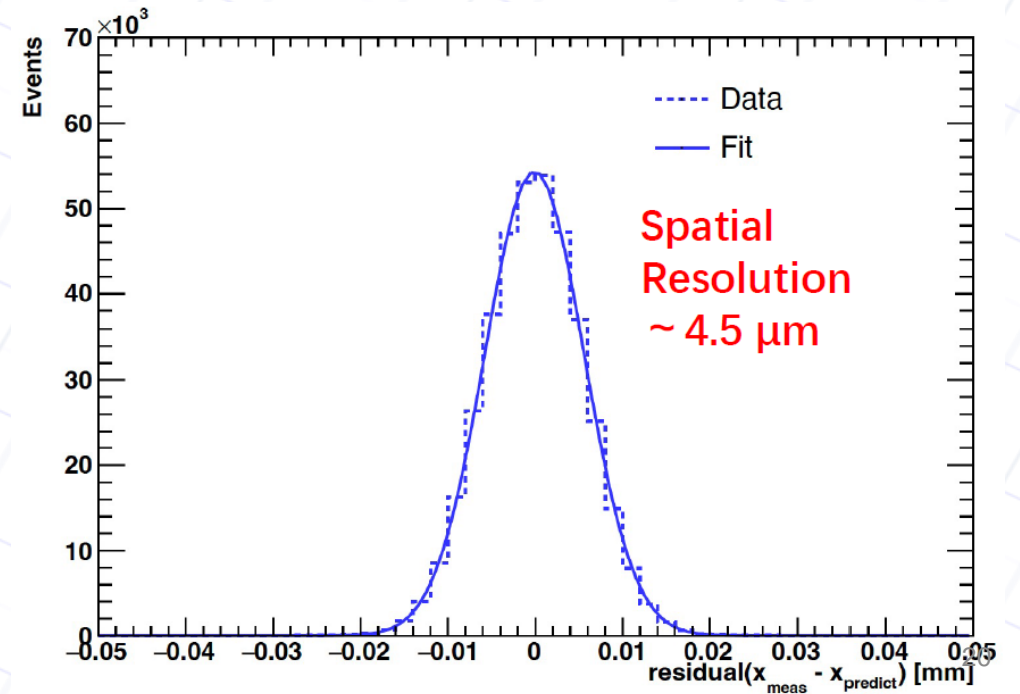
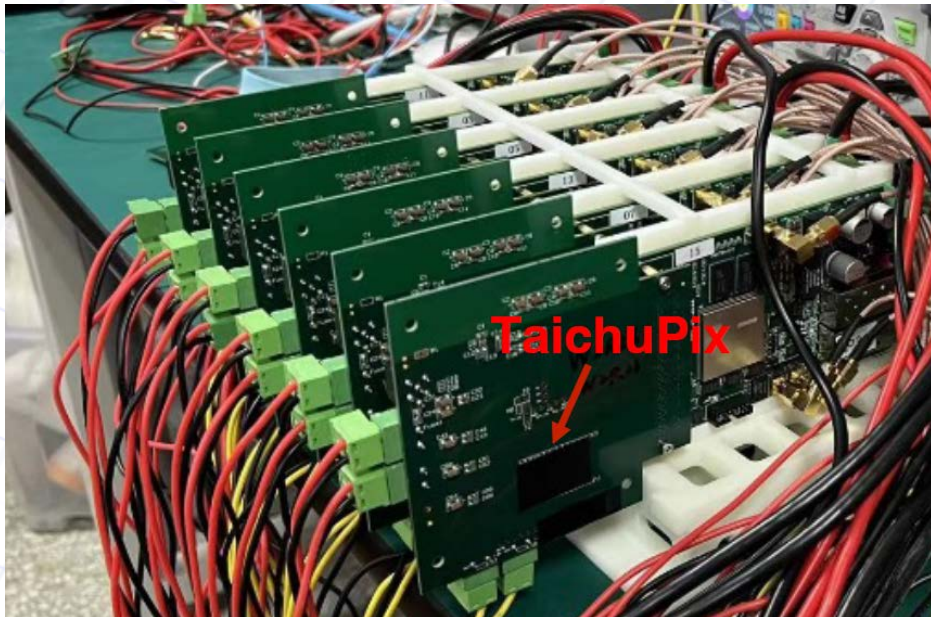
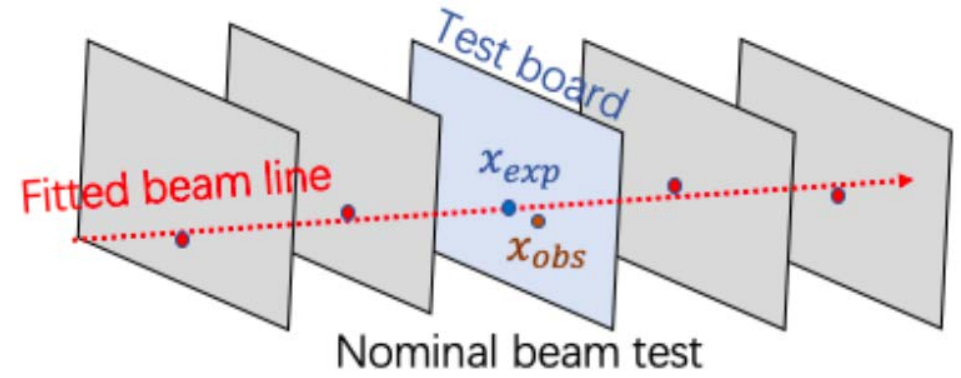




TaichuPix束流实验

用6个太初3芯片研制了束流望远镜

- 在德国DESY进行束流测试 (4-5 GeV 电子束), 1kHz rate
- 用其中5层太初芯片作为束流望远镜
- 其中一层为待测探测器 (DUT)
- 空间分辨率达到 $4.5 \mu\text{m}$





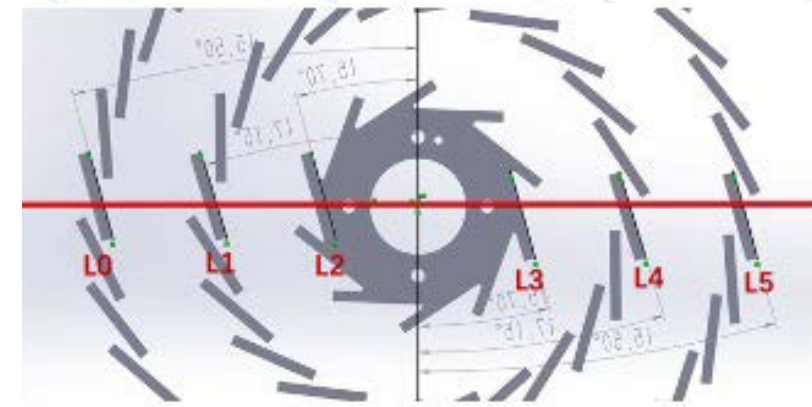
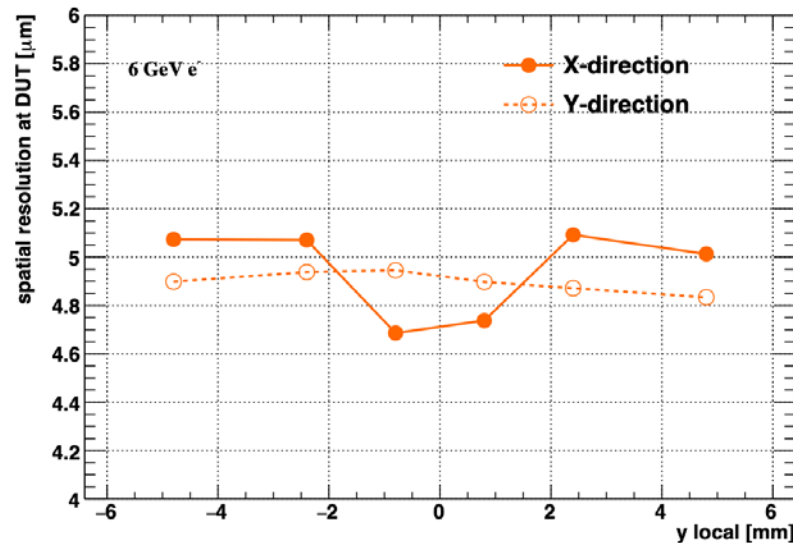
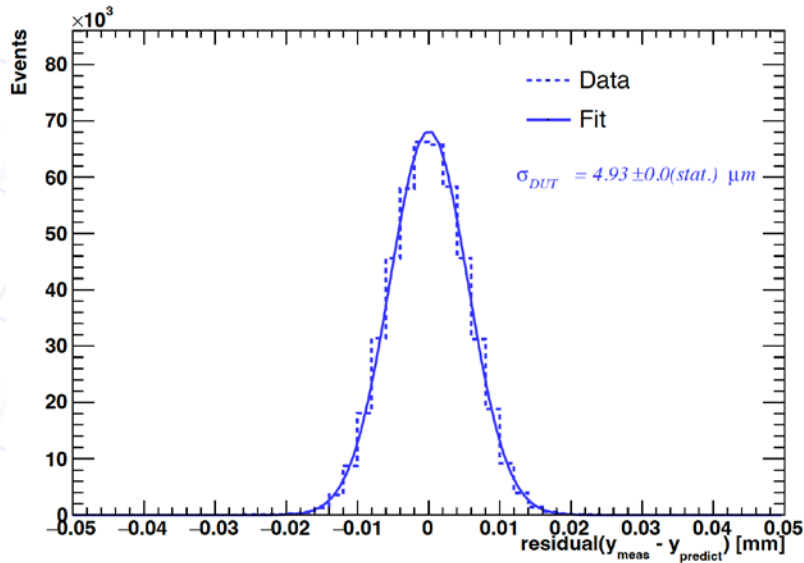
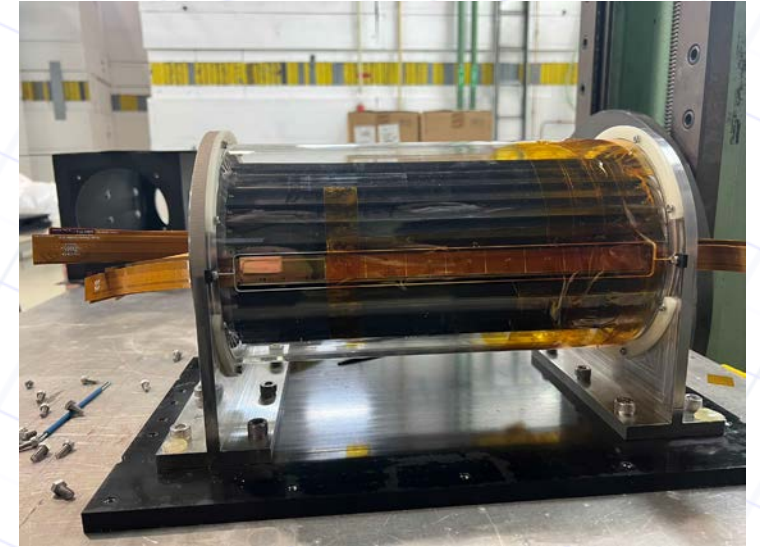
TaichuPix束流实验

研制了顶点探测器样机，2023年4月在德国DESY进行束流测试（5-6GeV电子束）

- 12个柔性电路板，24个太初芯片，同时工作
- 两周取数，记录了10亿条径迹

用其中一个单层太初芯片作为待测芯片（DUT）

- 顶点探测器样机的其他层作为束流望远镜
- 空间分辨率达到 $4.9\mu\text{m}$ (Y方向)





总结

进展:

- 完成了单层物质质量为**0.088%** X_0 的质子束流望远镜探测模块的设计与制作
- 搭建了基于MIMOSA28的多探测模块的测试系统，通过束流实验研究探测模块的性能和离线分析算法
- 搭建了TaichuPix束流望远镜系统及探测器模型，在DESY电子束上进行了测试，空间分辨好于 $5\mu\text{m}$

工作计划:

- 制作全部6层MIMOSA28束流望远镜，并进行进一步束流实验
- TaichuPix的进一步测试

Thanks for your attention !