

低质量双面型 硅像素探测模块 的性能研究

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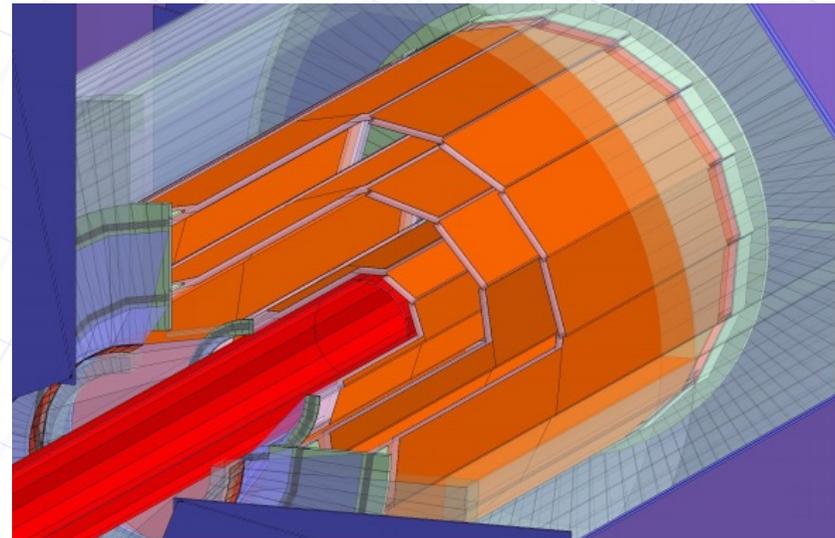
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目录

- double-sided ladder研制
- 束流实验
- 离线分析
- 总结



顶点探测器

- 大型环形正负电子对撞机实验 (Circular Electron Positron Collider, CEPC)
- 首要目标: 对Higgs粒子性质的精确测量
- CEPC**顶点探测器**的物理要求: 高精度的顶点分辨能力和带电粒子动量的精确测量,

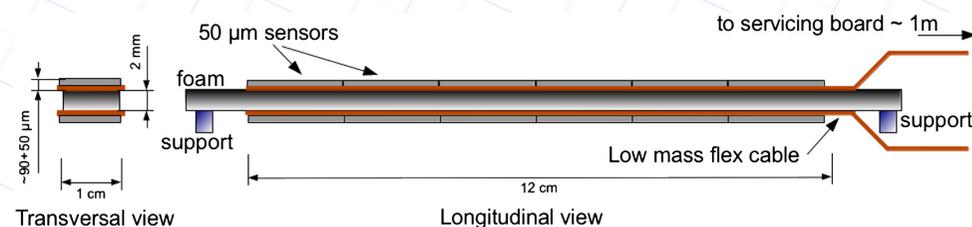
➤ 顶点探测器baseline设计

- 空间分辨率(最内层好于 $3\ \mu\text{m}$)
- 每层**物质质量**(每层低于 $0.15\%X_0$)
- 3层**double-sided layer**组成, 提供6个精确测量点

$$\sigma_{r\phi} = a \oplus b / (p(\text{GeV}) \sin^{3/2}\theta) \ (\mu\text{m})$$

□ 研究意义:

- ✓ 两层芯片共用一层支撑结构→**减小物质质量**→**减小多次库仑散射影响**
- ✓ 两层击中点(间距 2.4mm)→**提高空间分辨率, 易于校准, 提供角度信息等**
- ✓ 最内层可采用高空间分辨率+高时间分辨率芯片→**提高时间分辨能力和本底抑制能力**





探测模块

CEPC径迹探测系统Fast simulation:

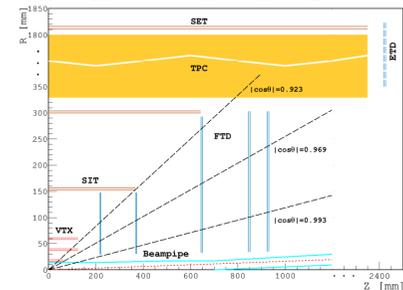
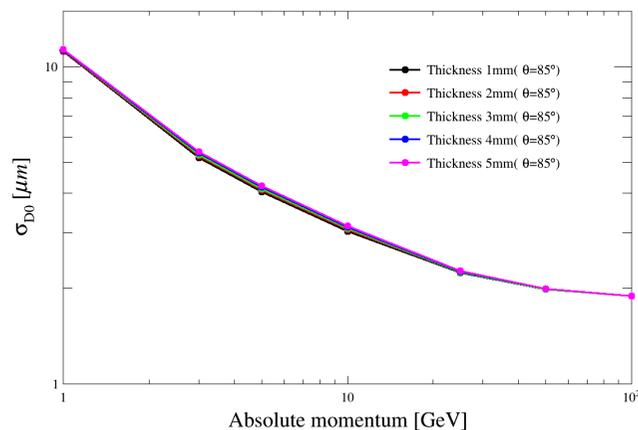
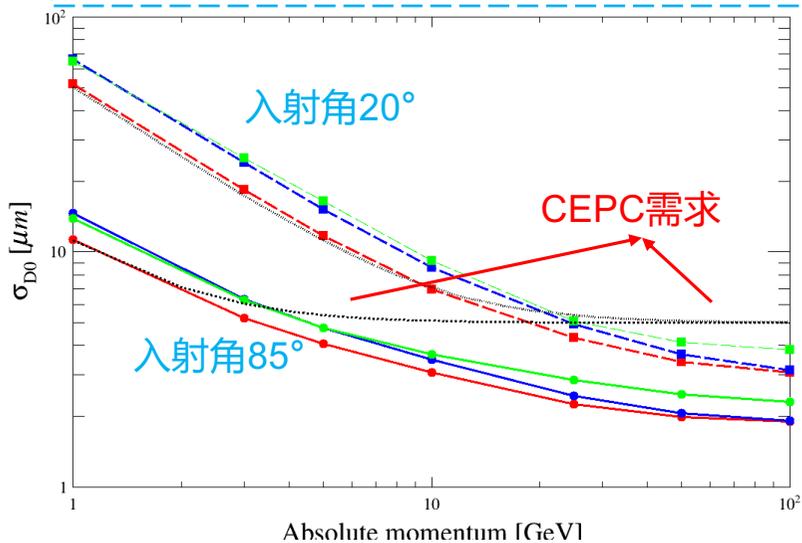
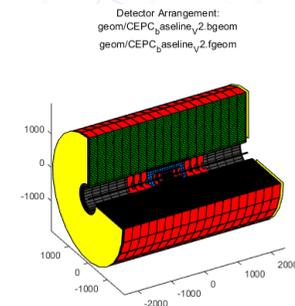
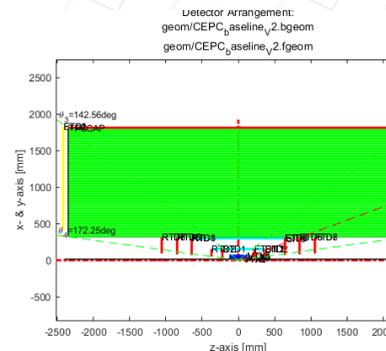
根据baseline设计, 基于LicDetectorToy(LDT)模拟

物质质量过大(每层0.30% X_0 , 蓝线)→不满足

single-sided设计(绿线)→不满足

double-sided设计(每层0.15%, 红线)→满足CEPC顶点探测器设计需求

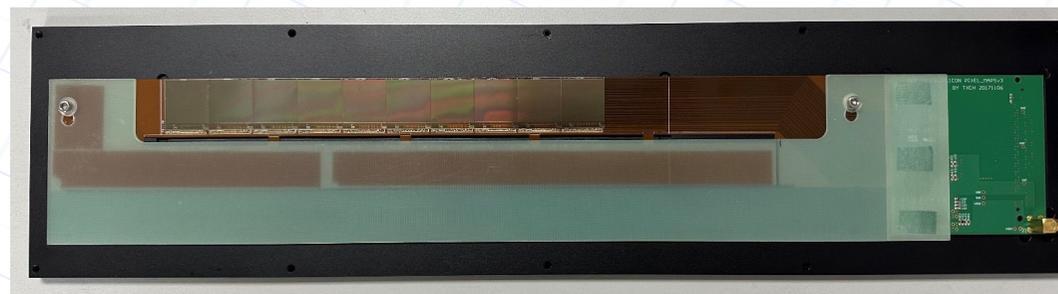
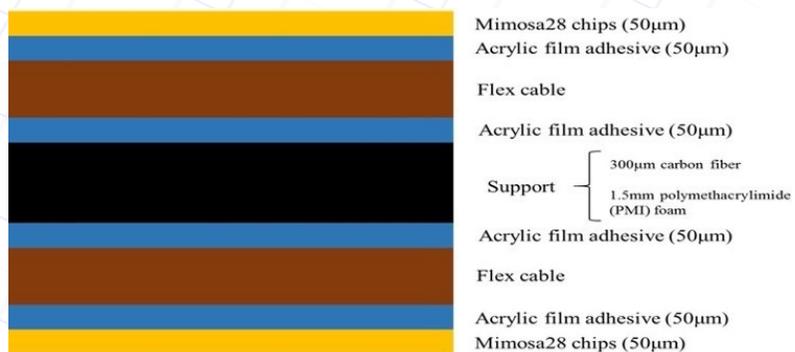
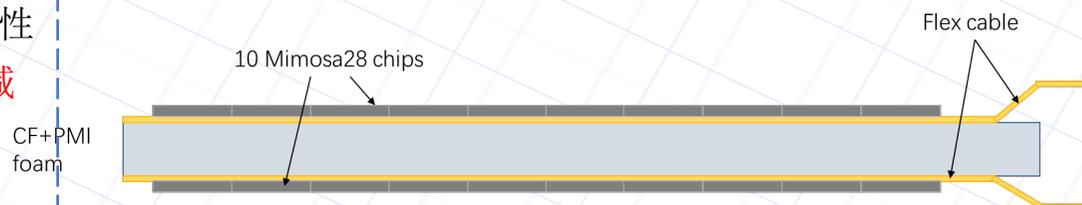
double-sided ladder间距→物质质量基本不变→顶点分辨率基本一致



探测模块

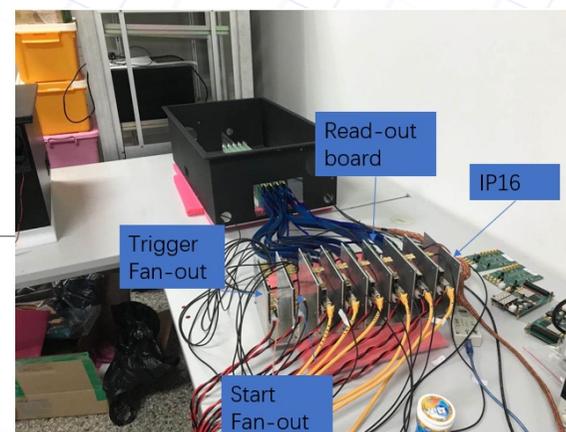
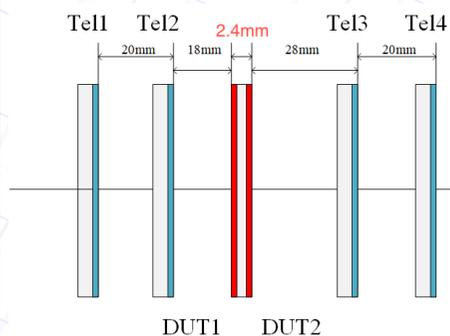
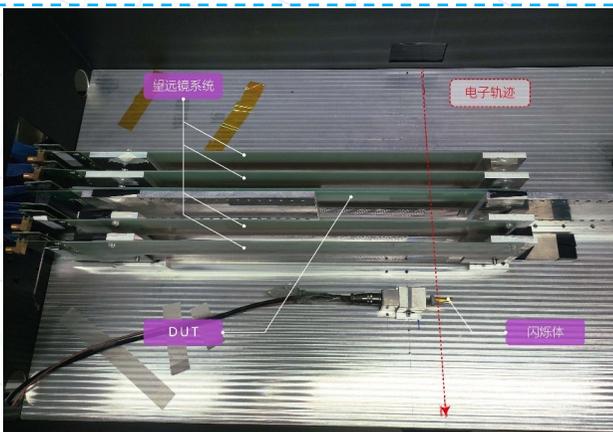
► double-sided ladder组成:

- 两层MIMOSA28芯片(50 μm)
- 两层柔性电缆(191.6 μm)
- 碳纤维支撑结构 (1.80mm)→满足结构稳定性
- 单层质量约0.24% X_0 →相比single-sided减少约35%
- 未来优化方案: 优化碳纤维支撑结构并减薄厚度, 采用镀铝走线等



束流实验

- **束流能量**: 经过铅皮散射后 $\sim 1.3\text{GeV}$, 能散大
- 六层探测模块组成探测器系统
 - 望远镜系统 (4层) + 待测模块 (DUT) (2层, 分别标记为DUT1, DUT2)
 - **double-sided ladder** 两层间距**2.4mm**
- 闪烁体 \rightarrow 提供触发信号
- 电子学系统:
 - 数据读出板+start控制和扇出板+外部时钟扇出板+触发信号扇出板





离线分析

□ 散射角分布

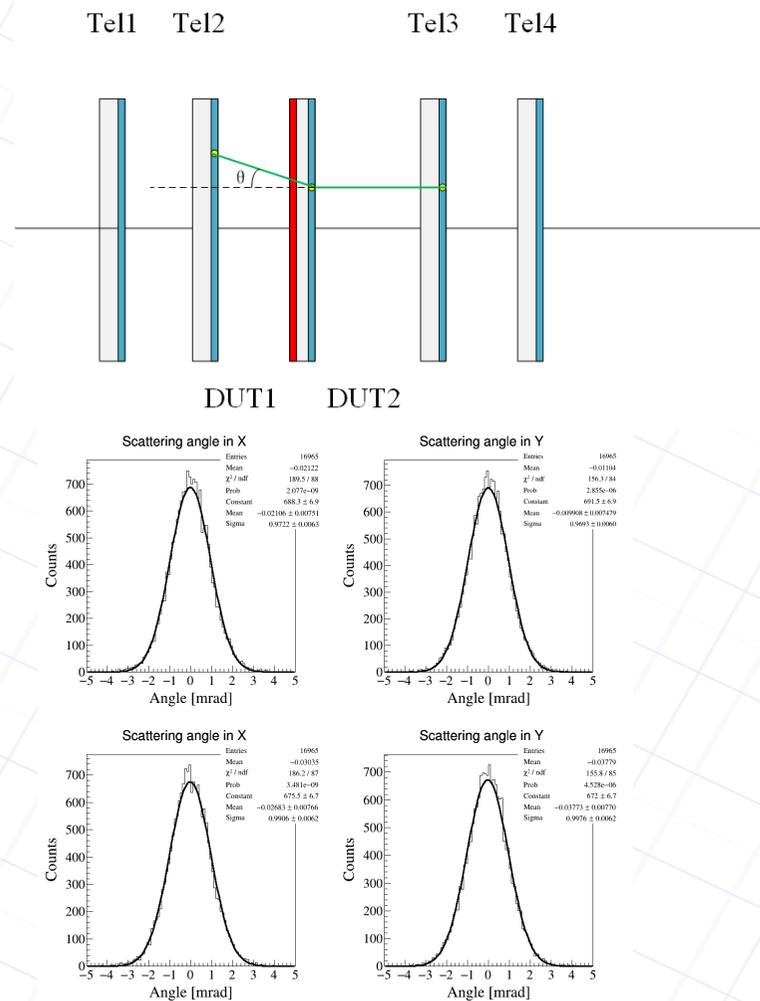
- Tel2+DUT2 → 径迹的入射角
- DUT2+Tel3 → 径迹的出射角
- 散射角分布 ~0.99mrad

DUT1
散射角

- 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

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





探测器校准

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:

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

➤ 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

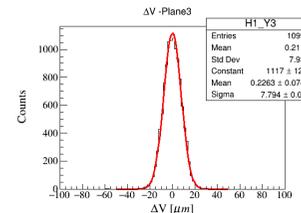
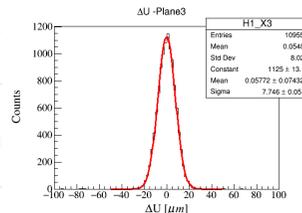
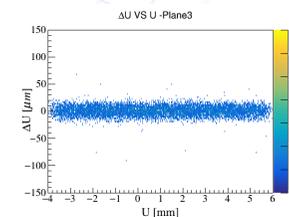
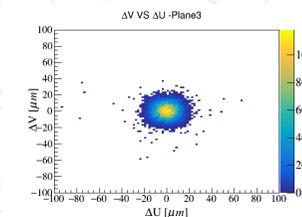
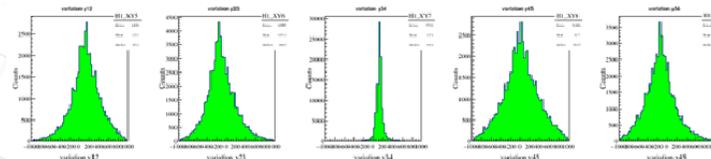
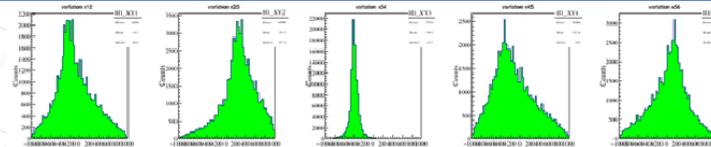
$$r_j = J_j^T M^T \quad r_j = \begin{pmatrix} u_j^c - u_j \\ v_j^c - v_j \end{pmatrix}$$

- 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

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



校准结果(阈值 5.5σ):

校准精度: $0.058\mu\text{m}(U)$, $0.2263\mu\text{m}(V)$



径迹拟合

径迹拟合(DUT击中不参与拟合):

最小卡方矩阵算法:

卡方函数

$$\chi^2 = \sum_{i=1, i \neq DUT}^N \frac{(M_i - P_i)^2}{\sigma_i^2} + \sum_{i=2}^{N-1} \left(\frac{(a_i + a_{i-1})P_i - a_{i-1}P_{i-1} - a_iP_{i+1}}{\Delta\theta_i} \right)^2$$

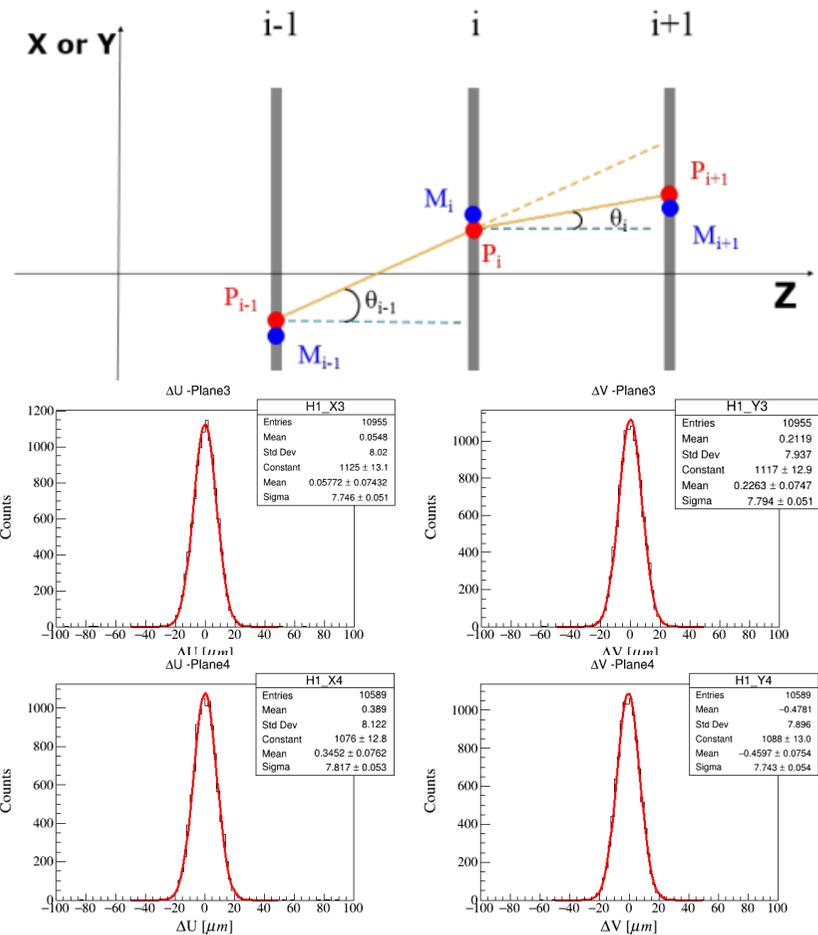
位置测量的不确定度+多次散射的不确定度

令卡方函数的一阶偏微分方程=0

$$\frac{\partial \chi^2}{\partial P_i} = 0, \quad i = 1, 2, \dots, N \rightarrow P = (A^T A)^{-1} A^T S$$

测量残差

DUT测量残差: $\sim 7.7\mu\text{m}$ (DUT1) $\sim 7.8\mu\text{m}$ (DUT2)



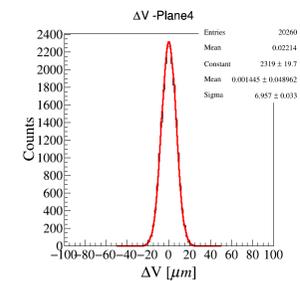
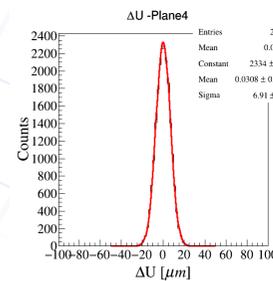
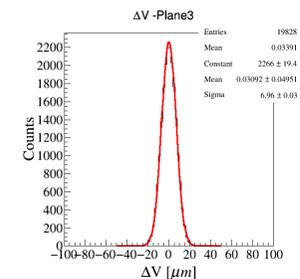
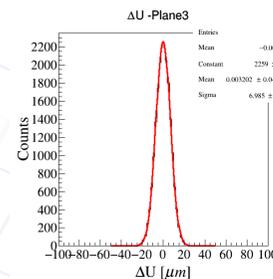
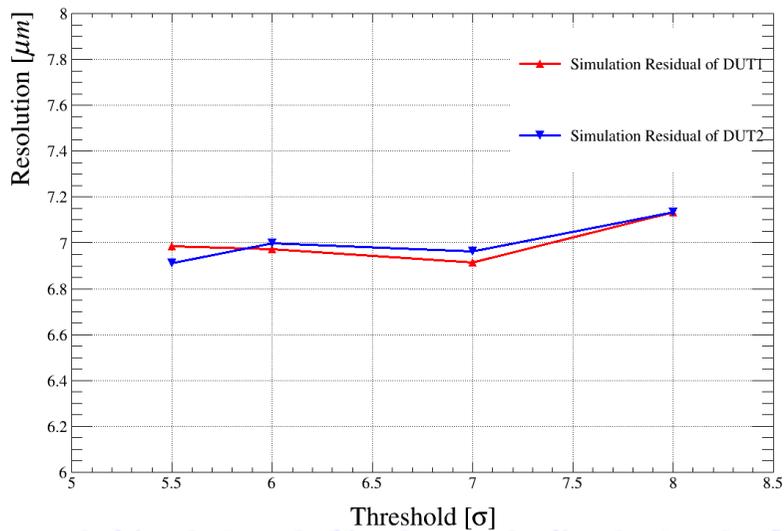
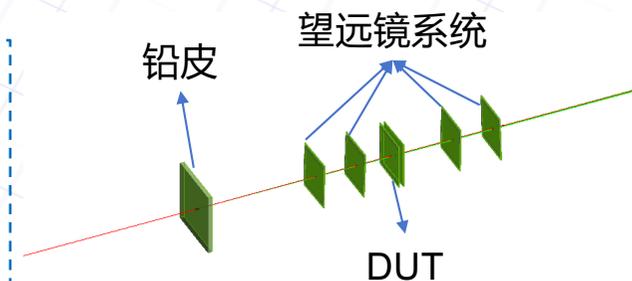


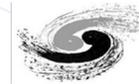
束流模拟

□ All-Pix²软件模拟束流测试

- 模拟测试系统由4层探测模块+ 1层双面探测模块组成
- 相同的离线分析算法
- DUT模拟所得测量残差(阈值 5.5σ) :

$\sim 7.0\mu\text{m}(\text{DUT1}), \sim 6.9\mu\text{m}(\text{DUT2})$





阈值影响

□ 簇团大小

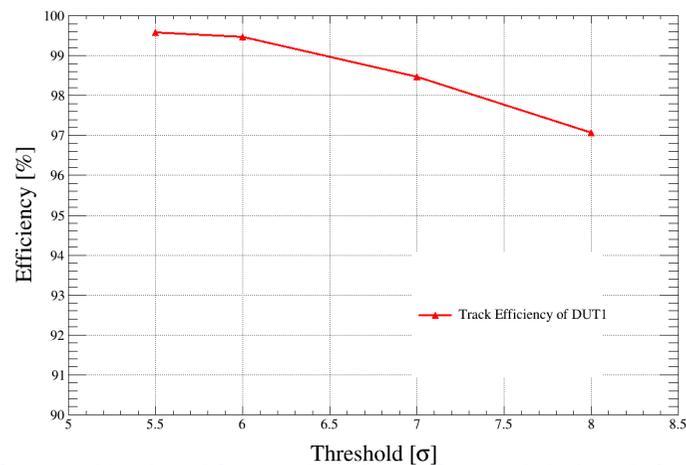
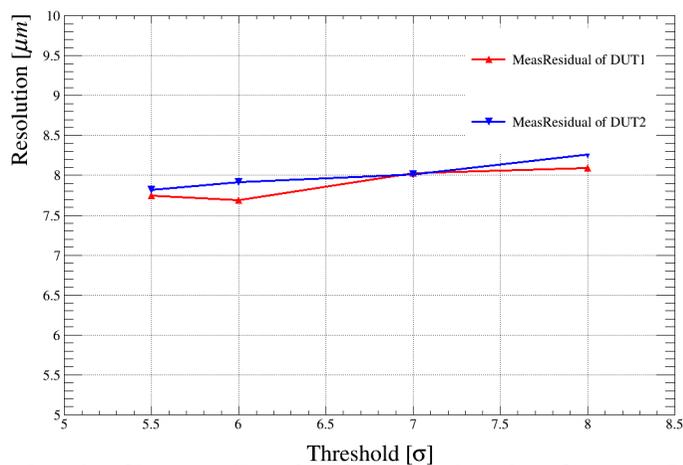
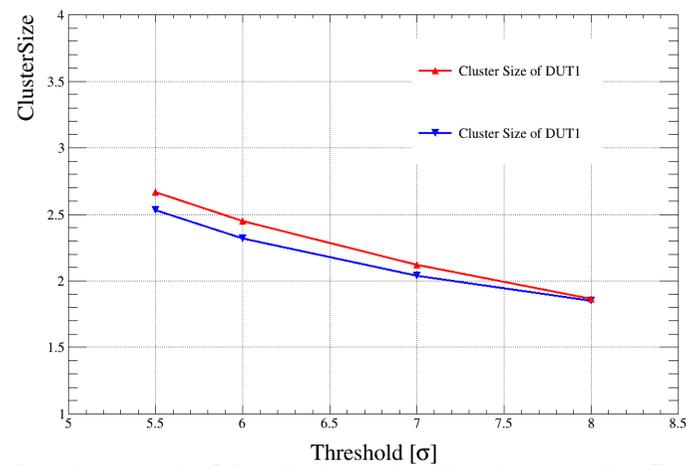
- 电荷共享效应→相邻着火像素重建为簇团
- 阈值→影响噪声和簇团大小→影响空间分辨率和探测效率

□ 测量残差

- 阈值增大，簇团减小→随阈值增大，测量残差增大

□ 探测效率

- $\varepsilon = \frac{\text{Track} \in \text{DUT} \subset \text{Referencetracks}}{\text{Track} \in \text{Referencetracks}}$
- ~99.5%，探测效率随阈值增大而减小





空间分辨率

□ 单点分辨率

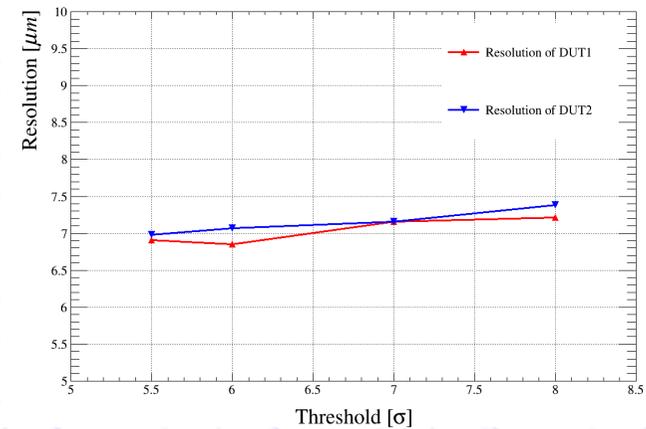
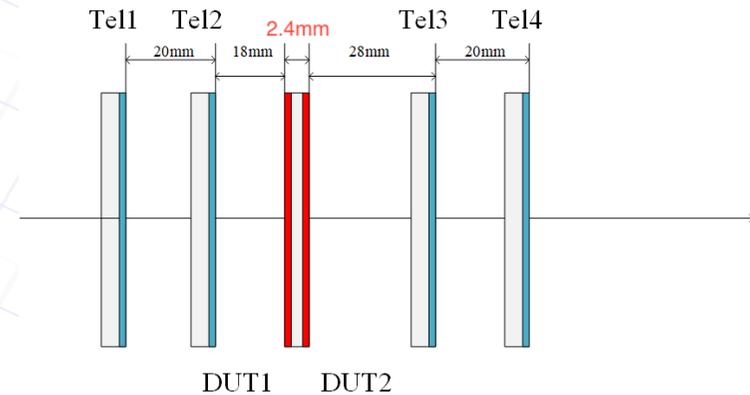
- DUT测量残差→单点分辨率+望远镜分辨率

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

- 望远镜Layout→计算系数k

$$k = \frac{\sigma_{tel}^2}{\sigma_{DUT}^2} = \frac{\sum_i^N z_i^2}{N \sum_i^N z_i^2 - (\sum_i^N z_i)^2} \Rightarrow \begin{cases} \sigma_{DUT}^2 = \frac{\sigma_{meas}^2}{1+k} \\ \sigma_{tel}^2 = \frac{k}{1+k} \sigma_{meas}^2 \end{cases}$$

- 单点分辨率: DUT1~6.9 μm , DUT2~7.0 μm (阈值5.5 σ)
- 望远镜分辨率: ~3.4 μm

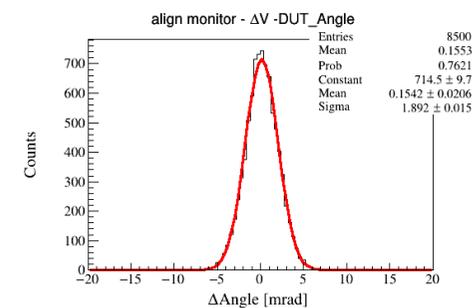
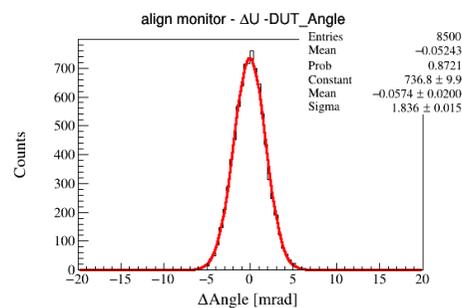
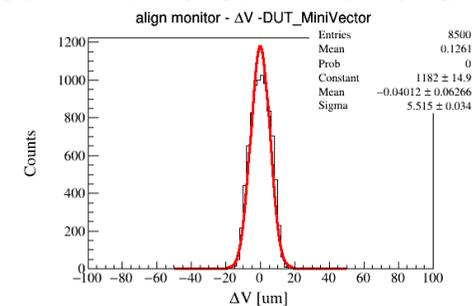
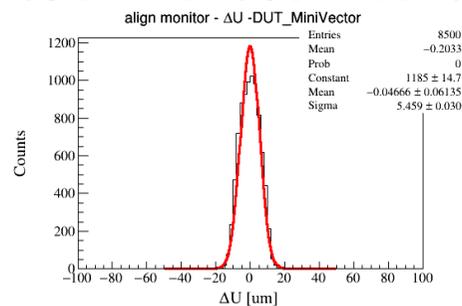
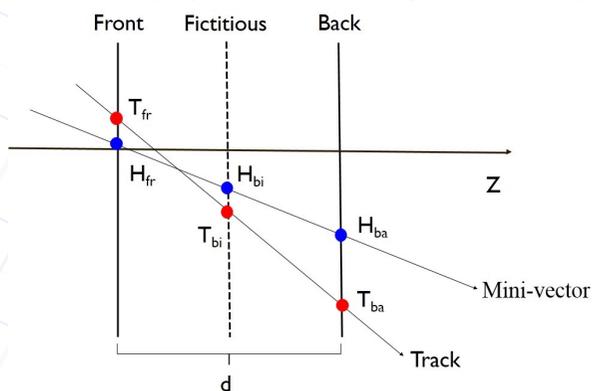




Doublesided

Double-sided

- DUT1+DUT2→组成mini-Vector
- 空间分辨率减少约30%, $\sim 4.9\mu\text{m}$ (扣除望远镜分辨率)
- DUT1+2→径迹穿过double-sided ladder的角度
→角分辨率 $\sim 1.9\text{mrad}$
- 优点: 空间分辨率更小, 可以获取径迹的角度信息→可能有助于寻迹和顶点重建





总结

- 完成了单层质量为**0.24%** X_0 的double-sided ladder的设计与制作
- 搭建了多探测模块的测试系统，通过束流实验验证探测模块的性能
- 研究束流实验的离线分析算法
- 分析结果表明，束流能量约1.3GeV且能散较大的情况下测得**double-sided ladder**的单点分辨率为**6.9 μm** ，探测效率**>99.5%**。利用两层击中信息的**Mini-Vector**分辨率为**4.9 μm** ，角度分辨率为**1.9mrad**

**Thanks for your
attention !**

Back up

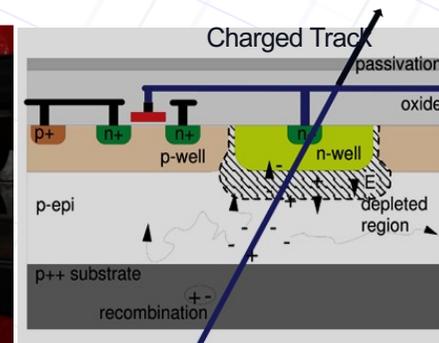
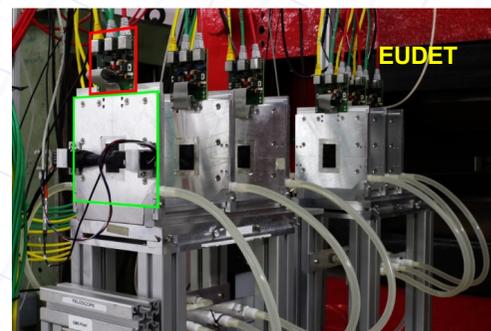
MAPS芯片

MIMOSA系列芯片:

- 法国IPHC研究所设计研发
- 标准CMOS工艺
- 数字型读出

MIMOSA28芯片

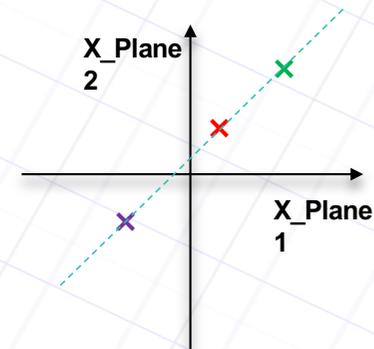
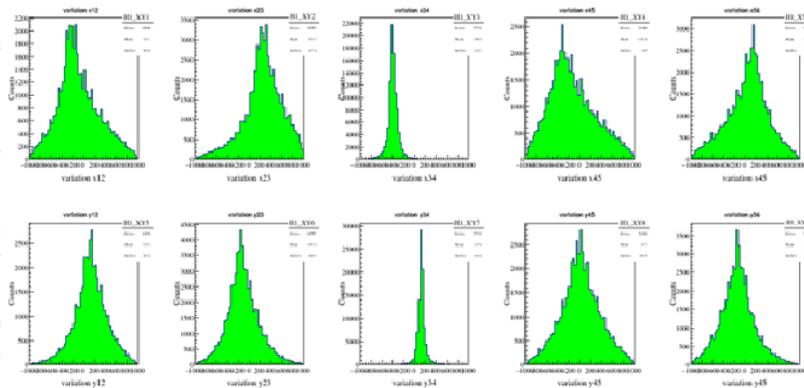
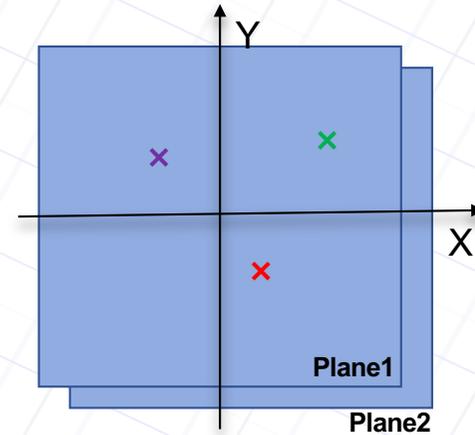
- 350nm工艺, 15 μm 外延层
- 灵敏区: 960(Column) \times 928(Row), 像素尺寸20.7 μm
- 已减薄至50 μm , 物质量~0.053%
- 读出时间 \rightarrow 每帧185.6 μs
- $\leq 150 \text{ mW/cm}^2$ 功耗 \rightarrow 可采用风冷



探测器校准

CoarseAlignment:

- 方法：径迹入射方向基本垂直于芯片→相邻两层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≈XY方向的偏移
- 相邻平面偏移基本在100-200 μm





径迹拟合

径迹拟合(DUT击中不参与拟合):

□ 最小卡方矩阵算法:

➤ 卡方函数

$$\chi^2 = \sum_{i=1, i \neq \text{DUT}}^N \frac{(M_i - P_i)^2}{\sigma_i^2} + \sum_{i=2}^{N-1} \left(\frac{(a_i + a_{i-1})P_i - a_{i-1}P_{i-1} - a_iP_{i+1}}{\Delta\theta_i} \right)^2$$

➤ 位置测量的不确定度+多次散射的不确定度

➤ 令卡方函数的一阶偏微分方程=0

$$\begin{pmatrix} \varepsilon_1 + \frac{a_1^2}{\Delta\theta_2^2} & \frac{-(a_1+a_2)a_1}{\Delta\theta_2^2} & \frac{a_1a_2}{\Delta\theta_2^2} & 0 & 0 & 0 \\ \frac{-(a_1+a_2)a_1}{\Delta\theta_2^2} & \varepsilon_2 + \frac{(a_1+a_2)^2}{\Delta\theta_2^2} + \frac{a_2^2}{\Delta\theta_3^2} & \frac{-(a_1+a_2)a_2}{\Delta\theta_2^2} + \frac{-(a_2+a_3)a_2}{\Delta\theta_3^2} & \frac{a_2a_3}{\Delta\theta_3^2} & 0 & 0 \\ \frac{a_1a_2}{\Delta\theta_2^2} & \frac{-(a_1+a_2)a_2}{\Delta\theta_2^2} + \frac{-(a_2+a_3)a_2}{\Delta\theta_3^2} & \frac{a_2^2}{\Delta\theta_2^2} + \frac{(a_2+a_3)^2}{\Delta\theta_3^2} + \frac{a_3^2}{\Delta\theta_4^2} & \frac{-(a_2+a_3)a_3}{\Delta\theta_3^2} + \frac{-(a_3+a_4)a_3}{\Delta\theta_4^2} & \frac{a_3a_4}{\Delta\theta_4^2} & 0 \\ 0 & \frac{a_2a_3}{\Delta\theta_3^2} & \frac{-(a_2+a_3)a_3}{\Delta\theta_3^2} + \frac{-(a_3+a_4)a_3}{\Delta\theta_4^2} & \frac{a_3^2}{\Delta\theta_3^2} + \frac{(a_3+a_4)^2}{\Delta\theta_4^2} + \frac{a_4^2}{\Delta\theta_5^2} & \frac{-(a_3+a_4)a_4}{\Delta\theta_4^2} + \frac{-(a_4+a_5)a_4}{\Delta\theta_5^2} & \frac{a_4a_5}{\Delta\theta_5^2} \\ 0 & 0 & \frac{a_3a_4}{\Delta\theta_4^2} & \frac{-(a_3+a_4)a_4}{\Delta\theta_4^2} + \frac{-(a_4+a_5)a_4}{\Delta\theta_5^2} & \varepsilon_5 + \frac{a_4^2}{\Delta\theta_4^2} + \frac{(a_4+a_5)^2}{\Delta\theta_5^2} & \frac{-(a_4+a_5)a_5}{\Delta\theta_5^2} \\ 0 & 0 & 0 & \frac{a_4a_5}{\Delta\theta_5^2} & \frac{-(a_4+a_5)a_5}{\Delta\theta_5^2} & \varepsilon_6 + \frac{a_5^2}{\Delta\theta_5^2} \end{pmatrix}$$

$$\sum_j A_{ij}P_j = S_i$$

$$A_{ij} = \frac{1}{2} \frac{\partial^2 \chi^2}{\partial P_i \partial P_j}, \quad S_i = \varepsilon_i M_i$$

$$P = (A^T A)^{-1} A^T S$$

$$S_i = \frac{1}{\sigma_i^2} M_i$$



径迹拟合

MiniVector:

$d=2.4\text{mm}$

单点分辨率: DUT1~ $6.9\mu\text{m}$,

DUT2~ $7.0\mu\text{m}$ →miniVector的 $\sigma_m=4.1\mu\text{m}$,实际空间分辨率~ $4.9\mu\text{m}$

$$\sigma_m^2 = \frac{(\sigma_{Front}^2 + \sigma_{Back}^2) d_m^2}{d^2} + \sigma_{tel}^2$$