

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

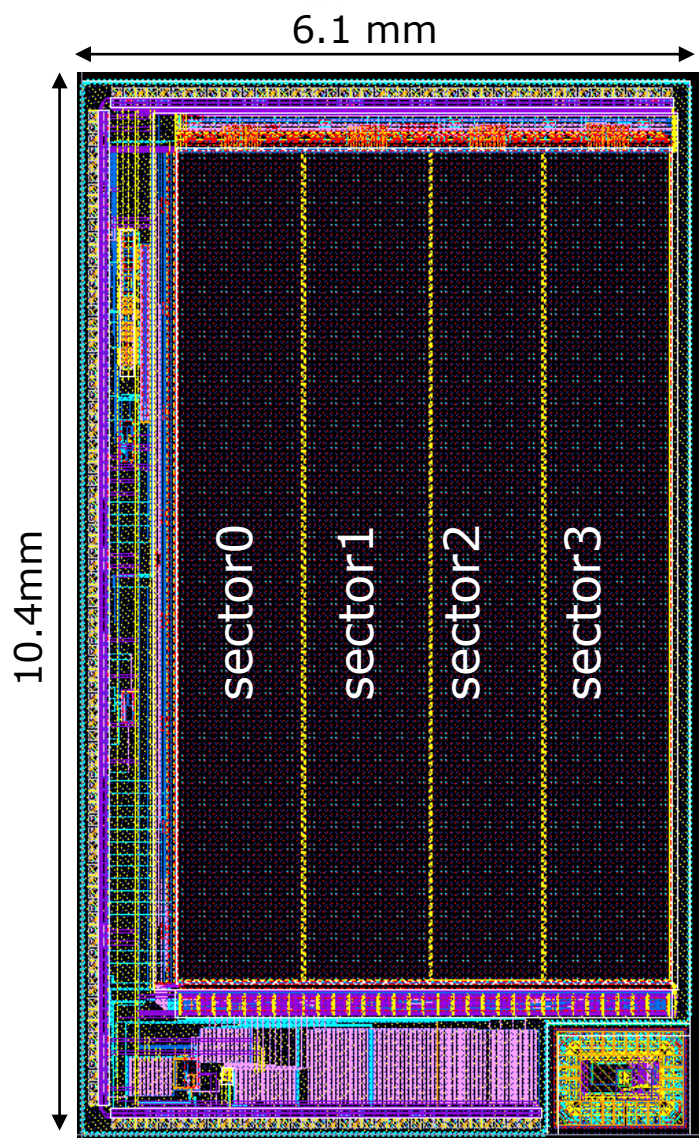
JadePix-3空间分辨率

卢云鹏

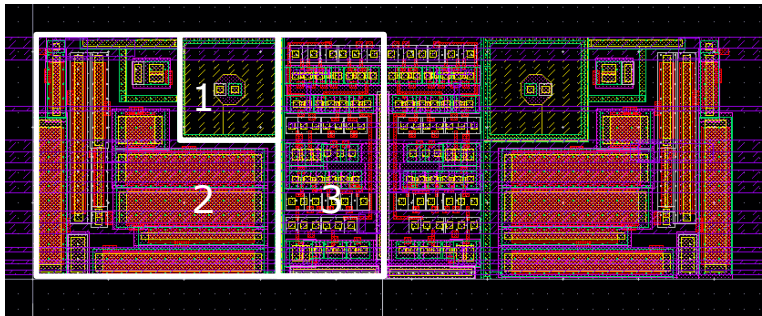
2025/8/25



Implementation of the pixel array



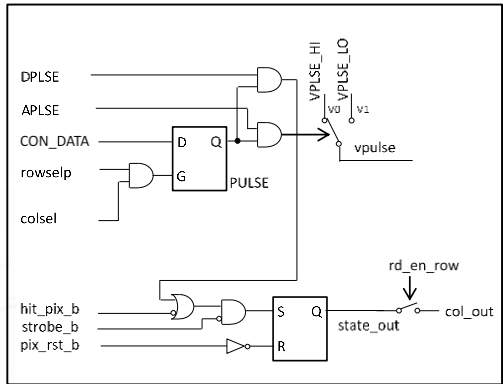
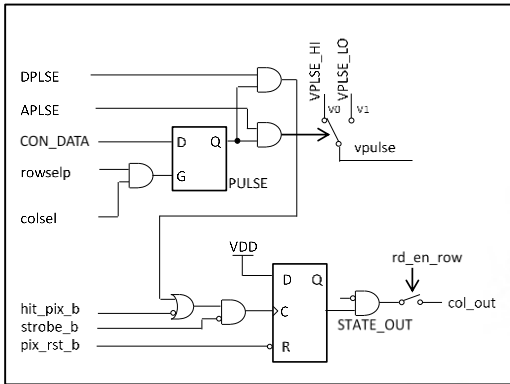
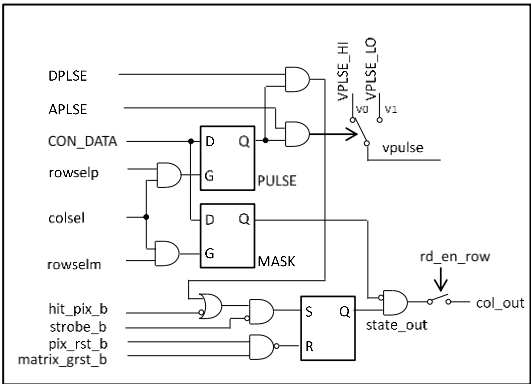
Sector	Diode	Analog	Digital	Pixel layout
0	2 + 2 μm	FE_V0	DGT_V0	16 $\times$ 26 μm^2
1	2 + 2 μm	FE_V0	DGT_V1	16 $\times$ 26 μm^2
2	2 + 2 μm	FE_V0	DGT_V2	16$\times$ 23.11 μm^2
3	2 + 2 μm	FE_V1	DGT_V0	16 $\times$ 26 μm^2



Minimal pixel footprint: **16 μm * 23.11 μm**

- 1: Sensing diode
- 2: Analog frontend
- 3: digital frontend

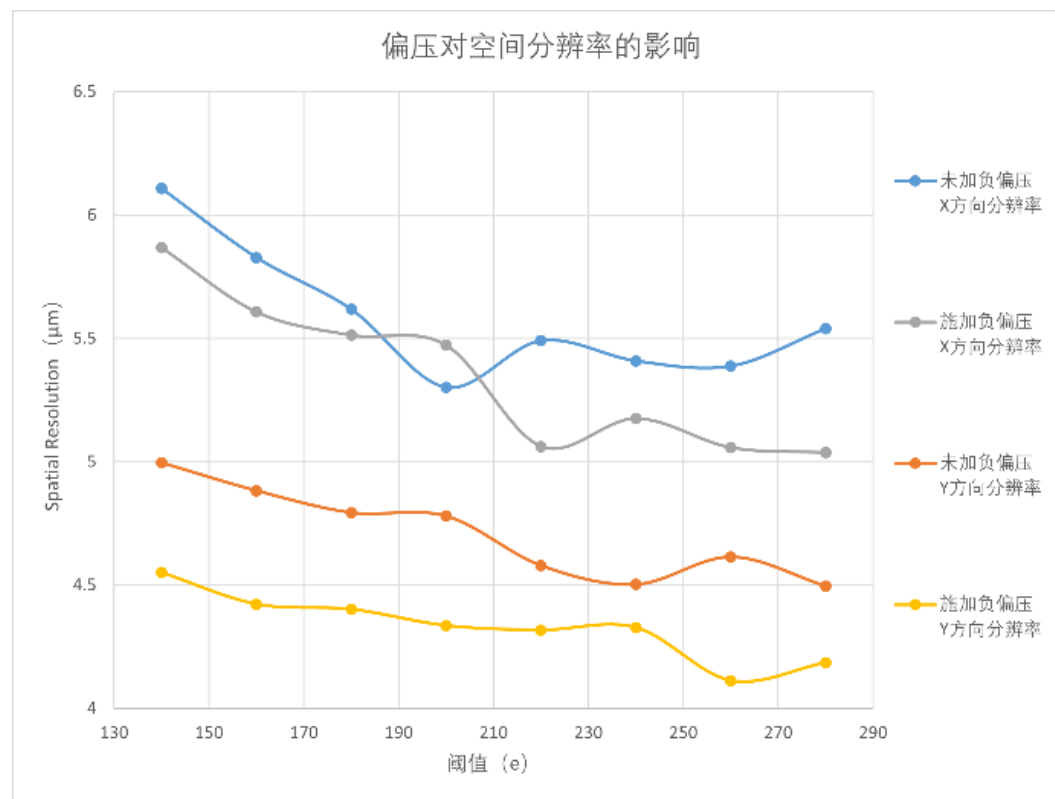
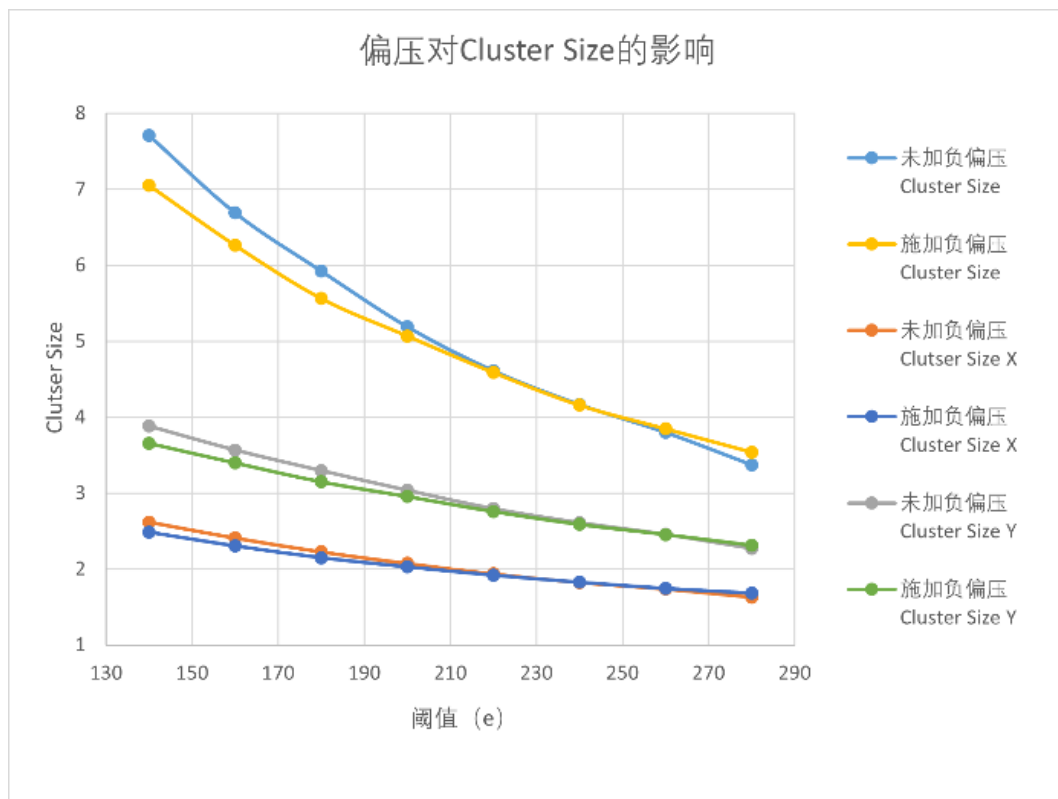
3 variants of digital frontend



TCAD Simulation

■ 300 um厚度芯片的空间分辨率与偏压的关系 (国科大王云翔)

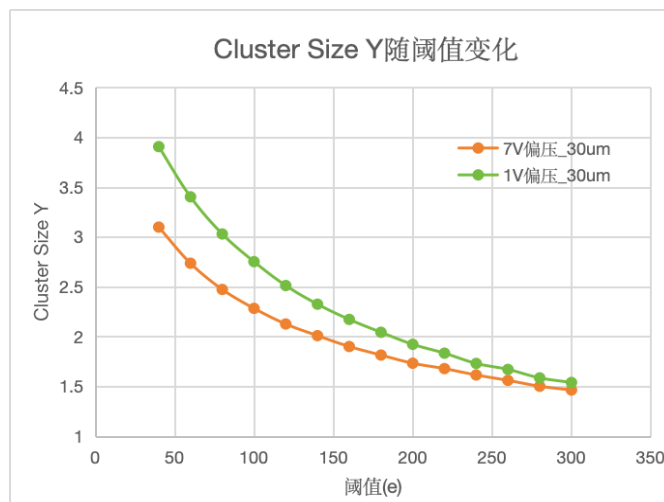
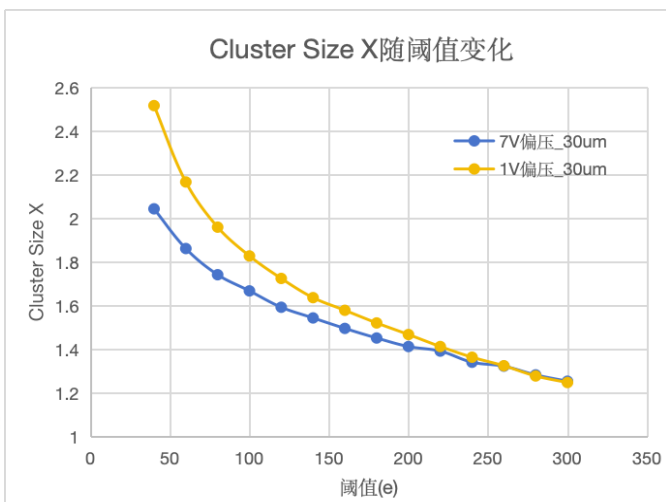
- 未施加偏压是指衬底=0V, Electrode=+1V
- 施加偏压是指衬底=-6V, Electrode=+1V



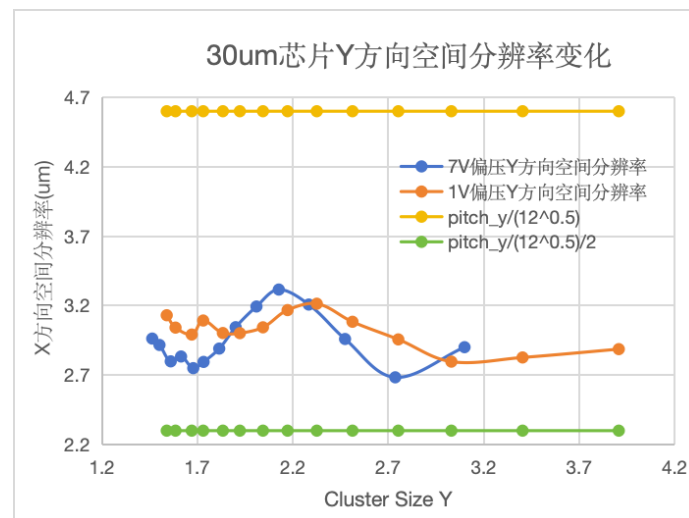
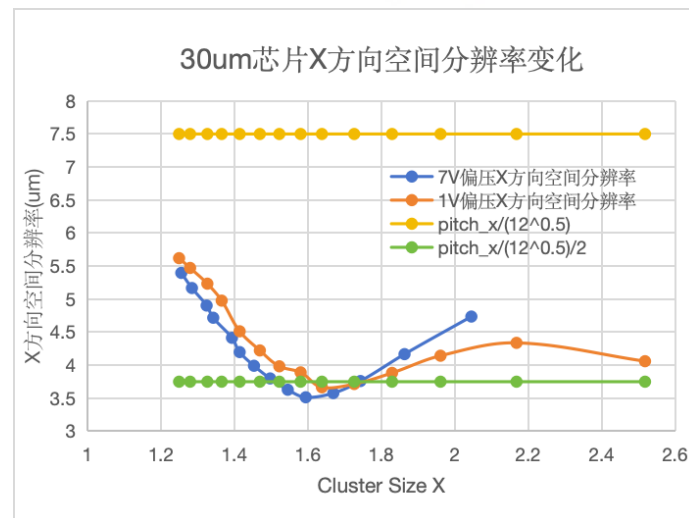
TCAD Simulation

■ 30 um厚度芯片的空间分辨率与偏压的关系 (国科大王安琪)

- 未施加偏压是指衬底=0V, Electrode=+1V
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JadePix-3芯片Cluster size X和Y随阈值的变化

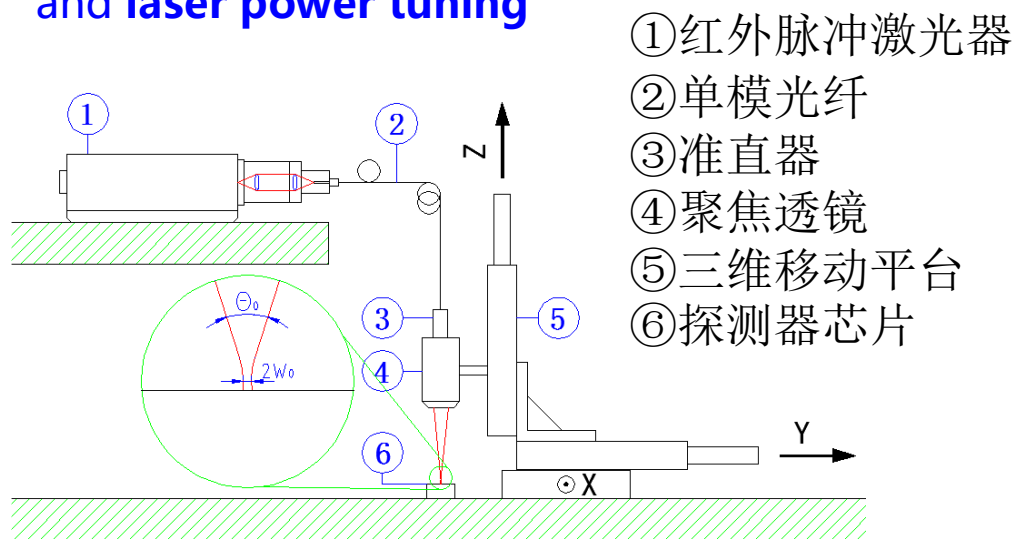


X和Y方向空间分辨率随Cluster size X和Y的变化

Measurement method of position resolution

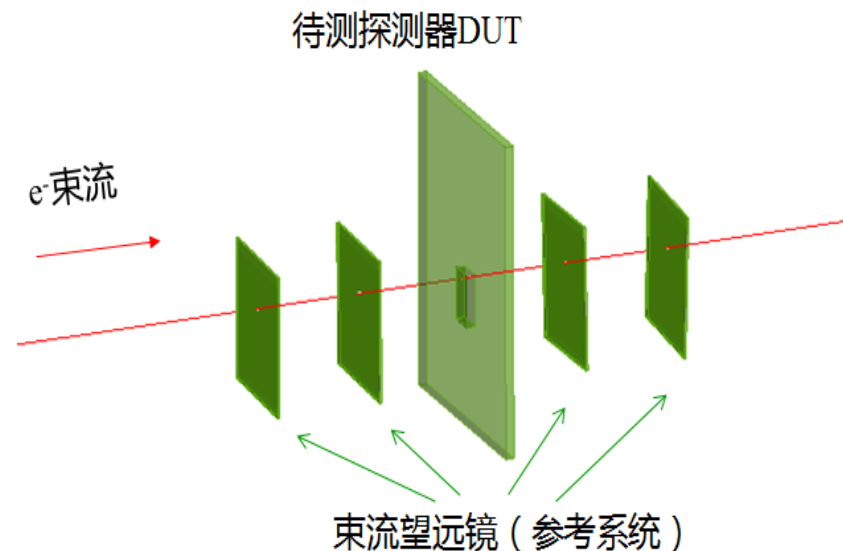
Pulsed laser beam

- Well controlled **scan of laser position** on a **single pixel**
 - One hit per laser pulse
 - Reference position given by the 3-D motion stage
 - σ of residual = measured - reference
 - Cluster size can be adjusted by threshold tuning and **laser power tuning**

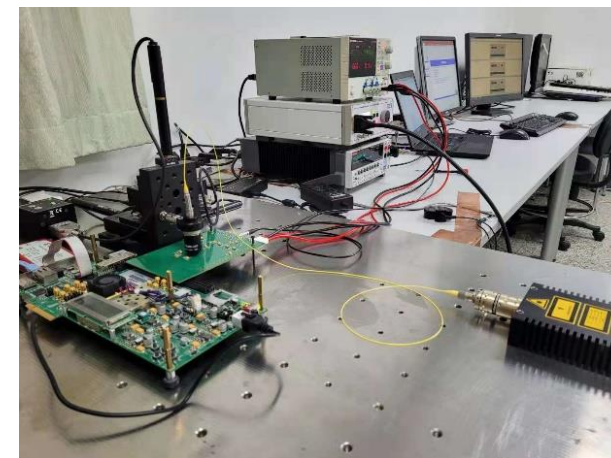
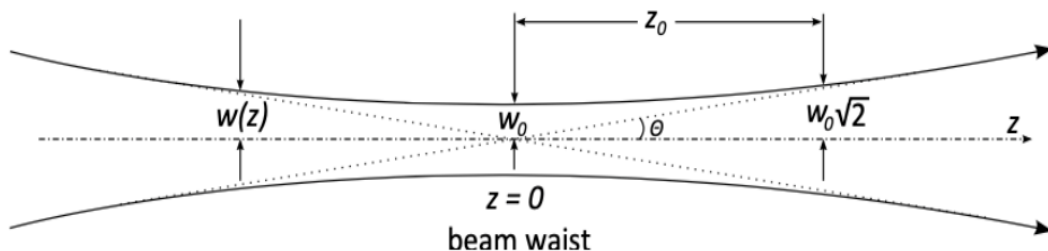


Charged particle beam

- Random hit position on the full matrix
 - One hit per particle
 - Reconstructed reference position by beam telescope
 - σ of residual = measured - reference
 - Cluster size can be adjusted by threshold tuning



Pulsed laser test



■ Laser beam characterization

- Wavelength: 1064 nm
- Beam waist $w_0 \sim 1.7 \mu\text{m}$
- Rayleigh range $z_0 \sim 8.5 \mu\text{m}$
- Divergence Angle $\theta = \sim 11^\circ$
- Laser pulse duration $\sim 100 \text{ ps}$

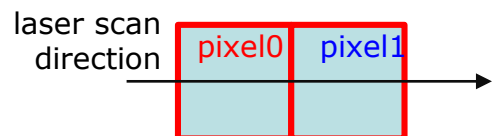
■ Laser power tune

- 0% : maximum power; 100% : minimum power
- For final results, use 92.7%, 92.9%, 93.3%, 93.5%, 93.7%
- 92.7% $\sim 4 \times \text{threshold}$ (threshold set to $\sim 220 \text{ e-}$)
- 93.7% $\sim 2 \times \text{threshold}$

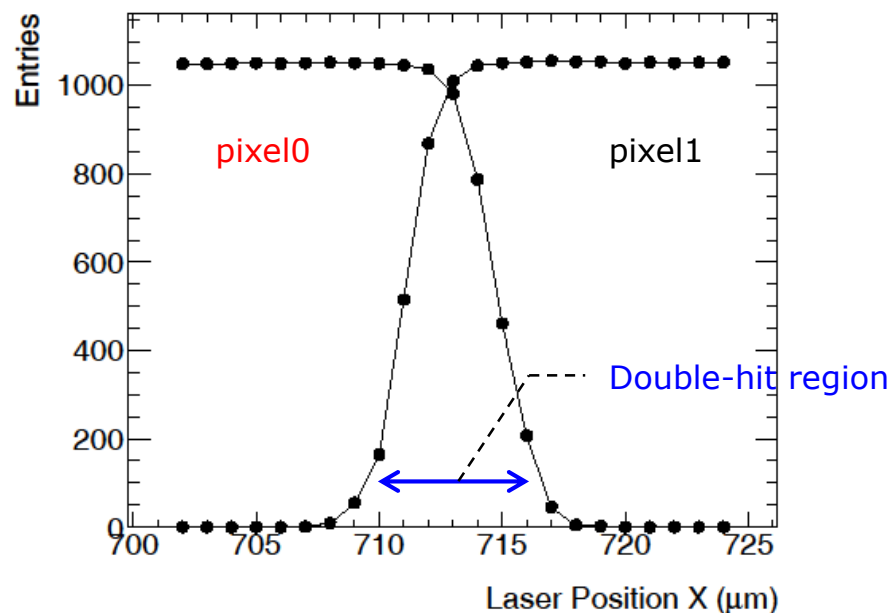
Measurement of position residual

■ 1-D scan of laser position

- Step = 1 μm and repeat 1000 at each step
- Laser power tune = 93.5% ($\sim 520\text{ e}^-$)



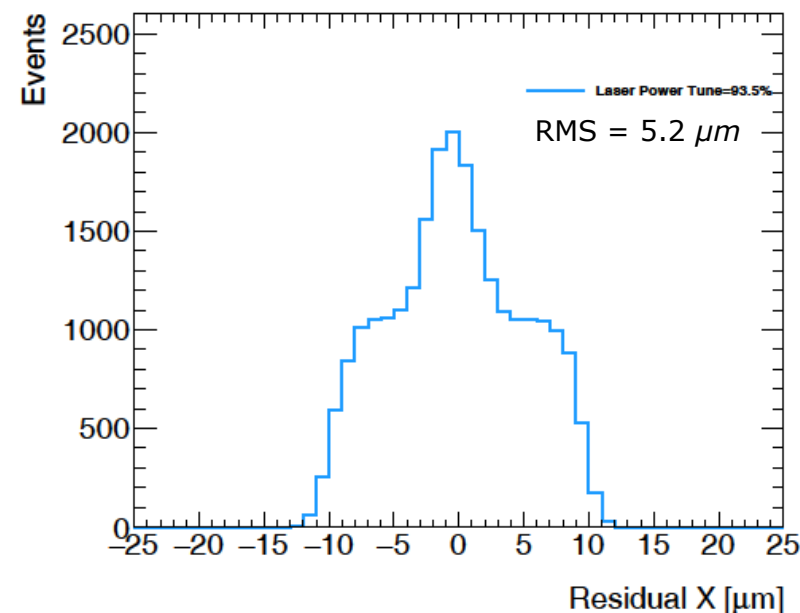
1-D scan of laser position



■ Distribution of position residual

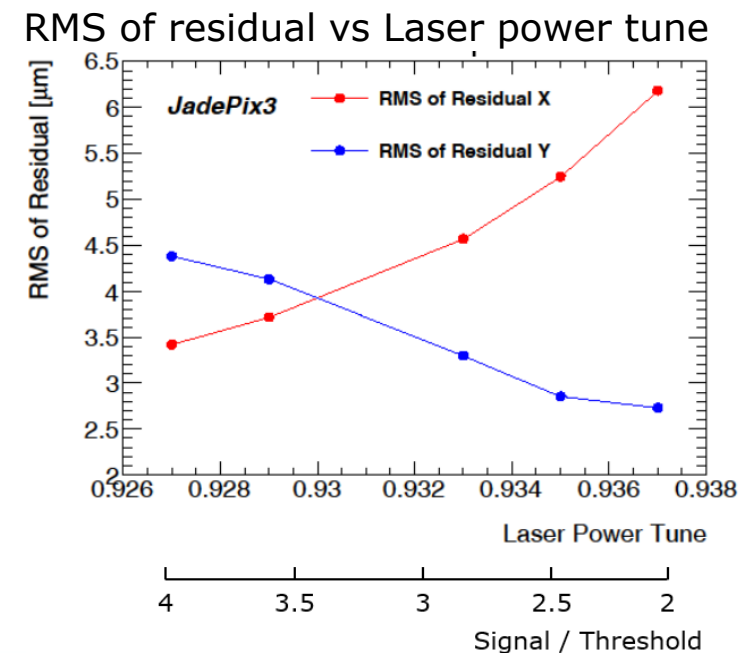
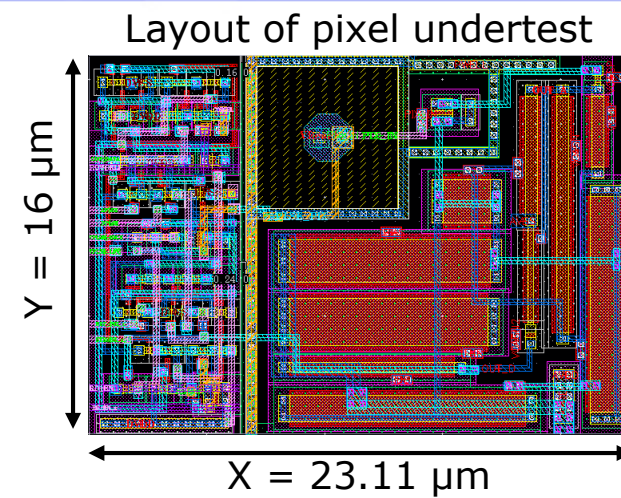
- Reference position: motion stage
 - Measured position: weight center of hit pixels
- ## ■ RMS taken as the 1-D spatial resolution

Residual distribution

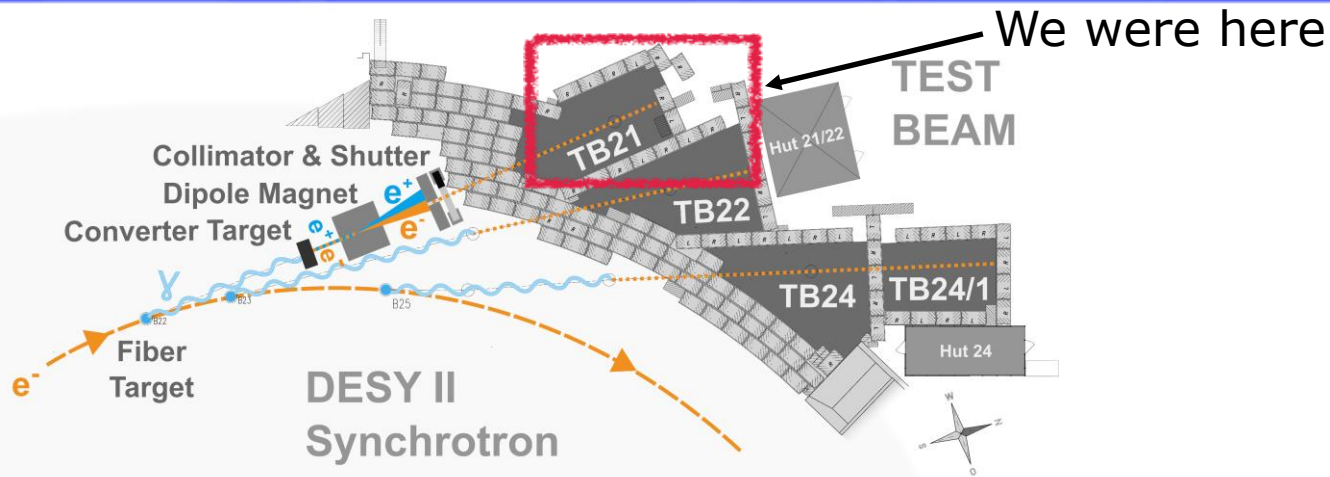


Impact of the Signal / threshold ratio

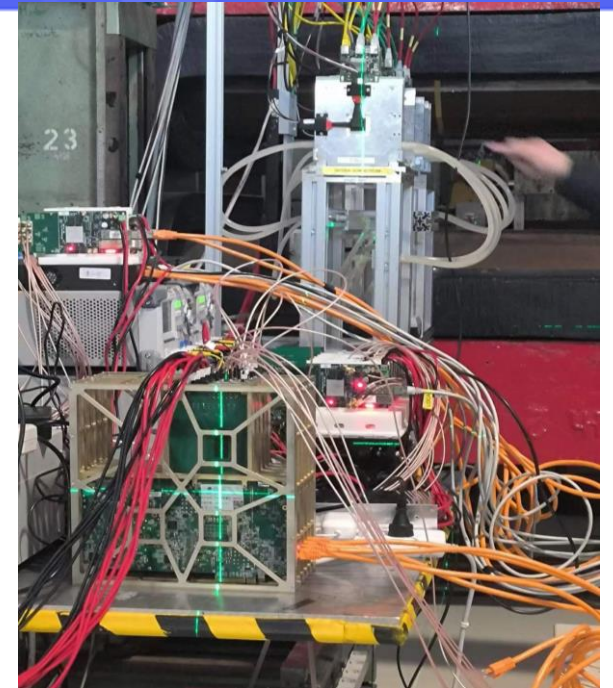
- Double-hit region varied with the sig. / thr. ratio
 - Threshold set to 220 e⁻
 - Laser power carefully tuned from 92.7% to 93.7%
- 1-D spatial resolution on X and Y
 - **Minimum 3.4 μm and 2.7 μm respectively**



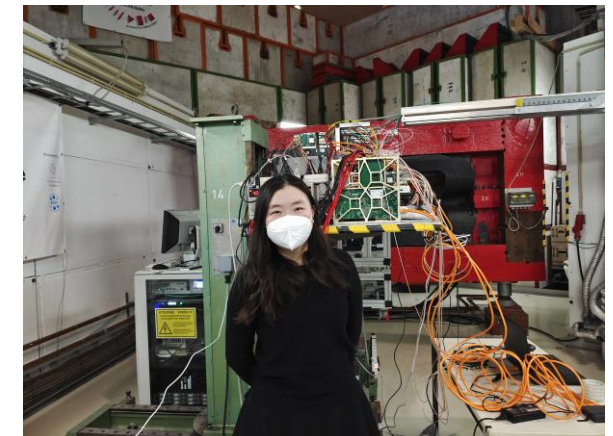
Test Setup at DESY TB21



- The electron or positron beams are converted bremsstrahlung beams from carbon fiber targets in the electron-positron synchrotron DESY II.
- up to 1000 particles per cm^2 and energies from 1 to 6 GeV, an energy spread of $\sim 5\%$ and a divergence of ~ 1 mrad.
- 5 layers of MIMOSA
- 6 layers of TaichuPix-3
- 5 layers of JadePix-3, **remote operation from Beijing**

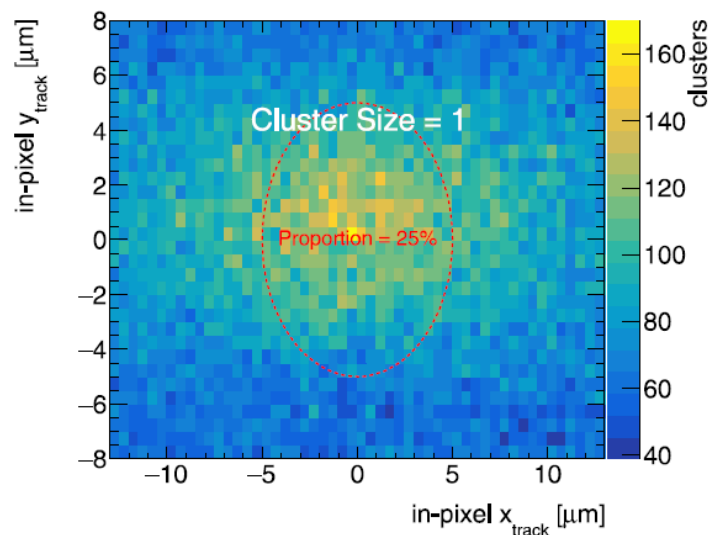


Test Setup @DESY Dec.2022

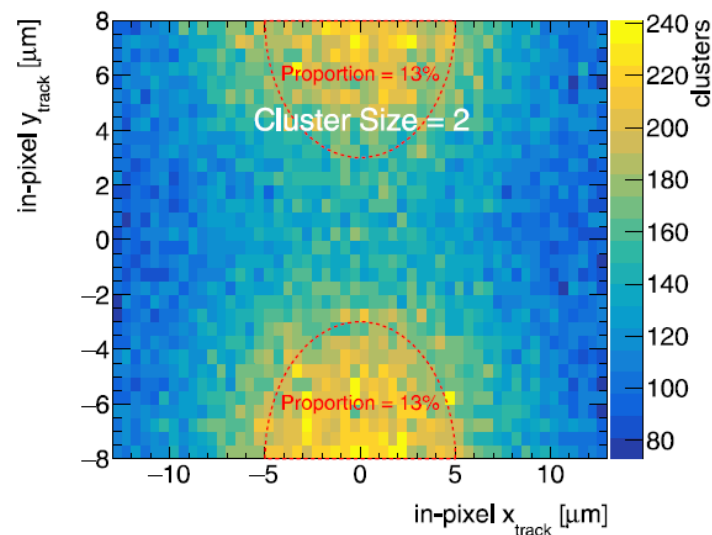


不同CS事例的位置分布

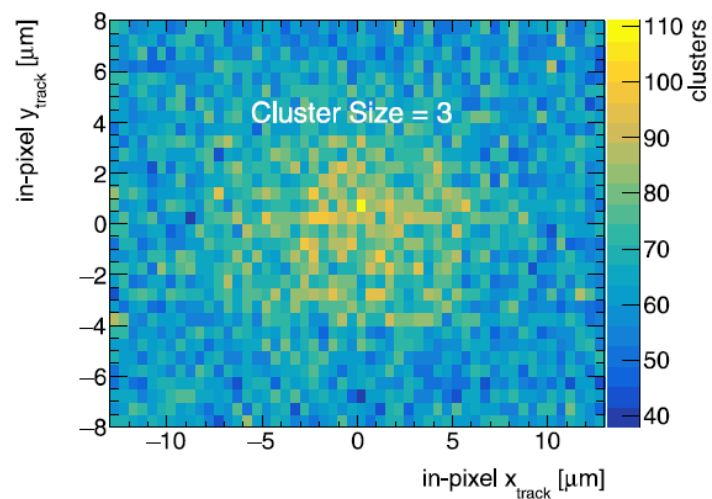
- CS=1, 中心
- CS=2, 上下边
- CS=3, 见下页
- CS=4, 四角



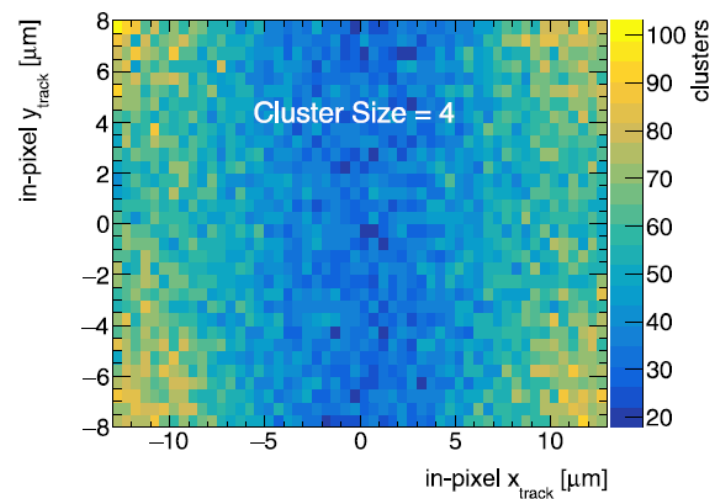
(a)



(b)



(c)

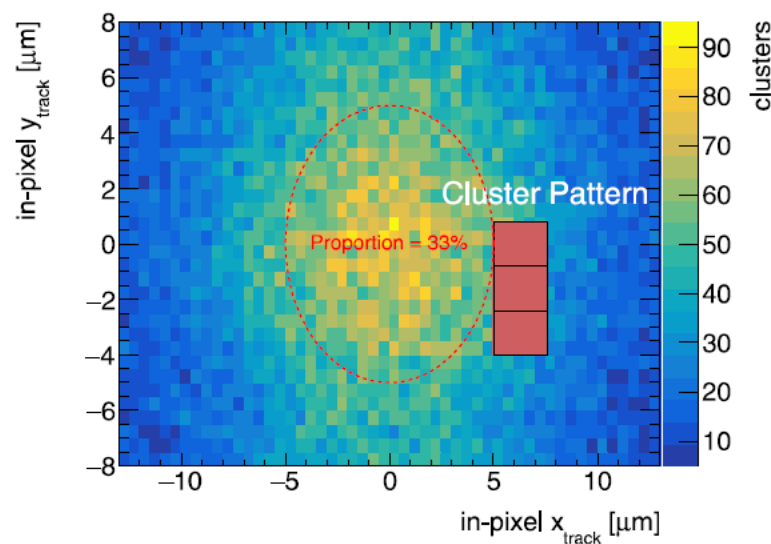


(d)

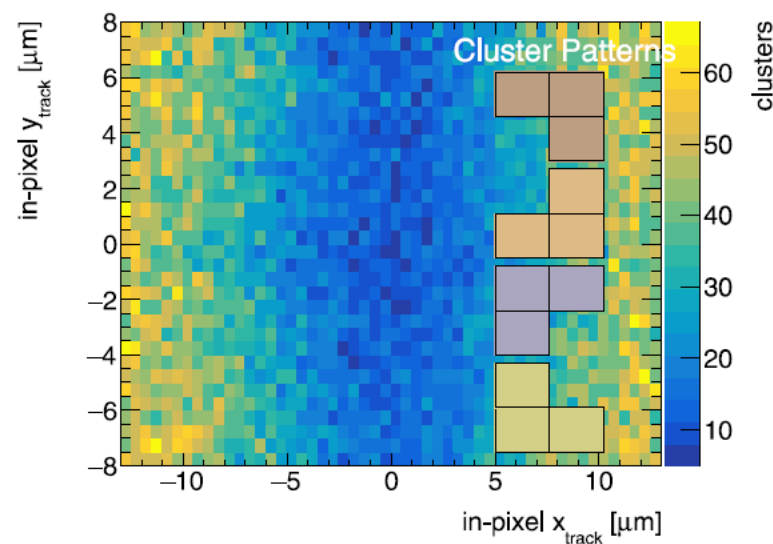
不同CS事例的位置分布

■ CS=3的两种主要Pattern

- Pattern (a)占53.3%
- Pattern (b)占46.3%



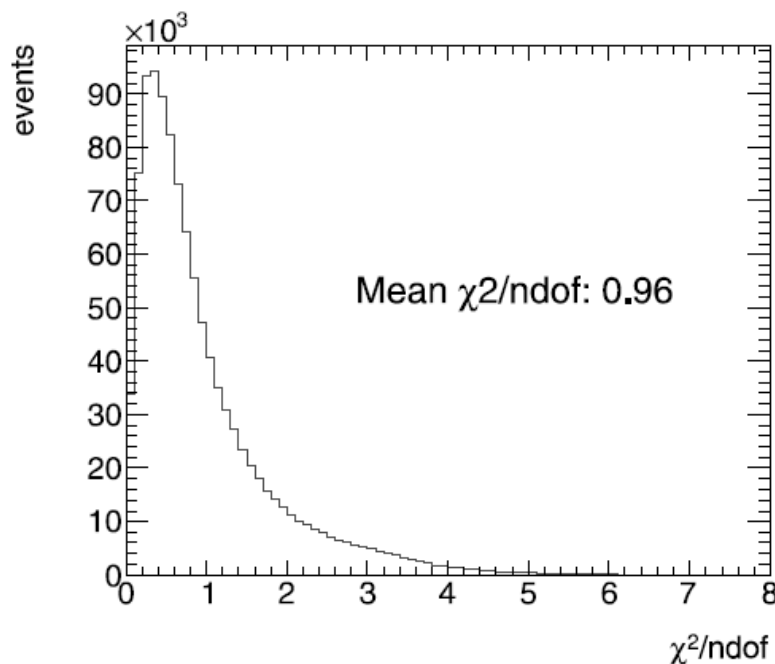
(a)



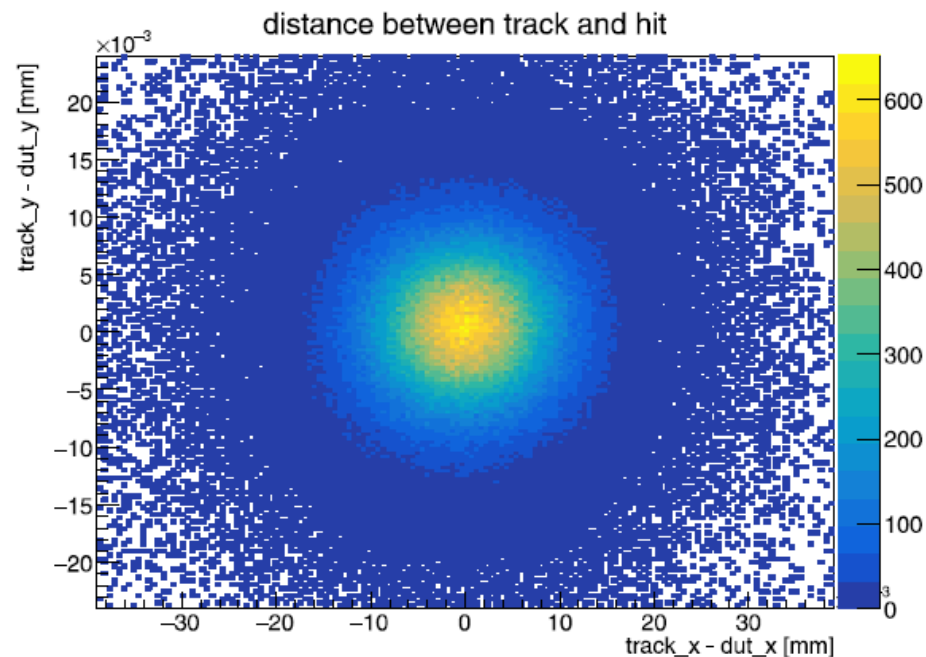
(b)

Tracking Performance

- χ^2/n_{dof} 分布, 平均值为0.96
 - 较低的 χ^2/n_{dof} 表明径迹重建效果很好
- DUT上的位置残差分布集中在1个像素宽度之内



(a)

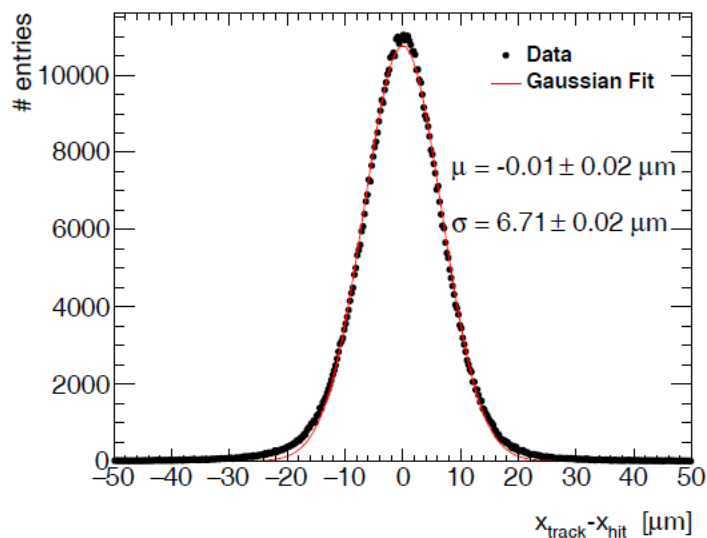
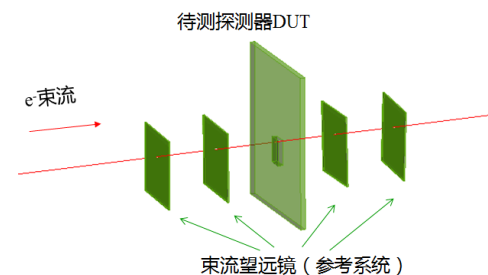


(b)

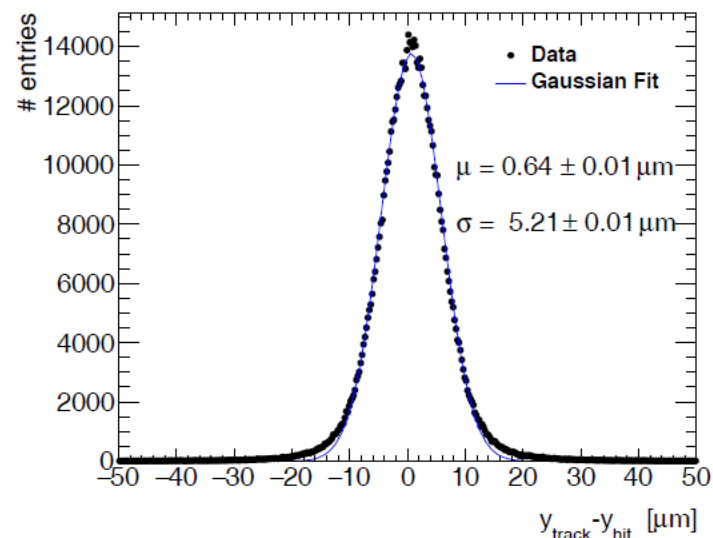
Fig. 9. Assessment of alignment performance through (a) the distribution of χ^2/n_{dof} of track fitting and (b) the distribution of the distance between the track and the hit. Experiment parameters: beam energy = 5.8 GeV, threshold = 200 e^- .

无偏残差分布

- 以4层作为reference, 重建径迹
- 以中间层作为DUT, 计算残差



(a)



(b)

图 4.10 x 方向和 y 方向无偏残差分布。数据以黑色圆点表示，高斯拟合为图中红色/蓝色线。

实验参数：束流能量 = 5.8 GeV，阈值 = 200 e^- 。

DUT与Telescope分辨率

- 上页的无偏残差分布可进一步分解为DUT和Telescope分辨率
- 满足以下条件，即可用公式4.4或4.5
 - Reference与DUT的分辨率相同
 - Reference在DUT两侧对称分布
- K值由层间距确定

$$\sigma_{DUT}^2 = \sigma_{plane}^2 = \frac{\sigma_{meas}^2}{1+k} \quad (4.4)$$

$$\sigma_{tel}^2 = \frac{k}{1+k} \sigma_{meas}^2 \quad (4.5)$$

标称阈值下的分辨率

	X方向	Y方向
Measurement	6.7 um	5.2 um
Telescope	3.0 um	2.3 um
DUT	6.0 um	4.7 um

击中位置对残差的影响

X方向的像素边缘有明显影响

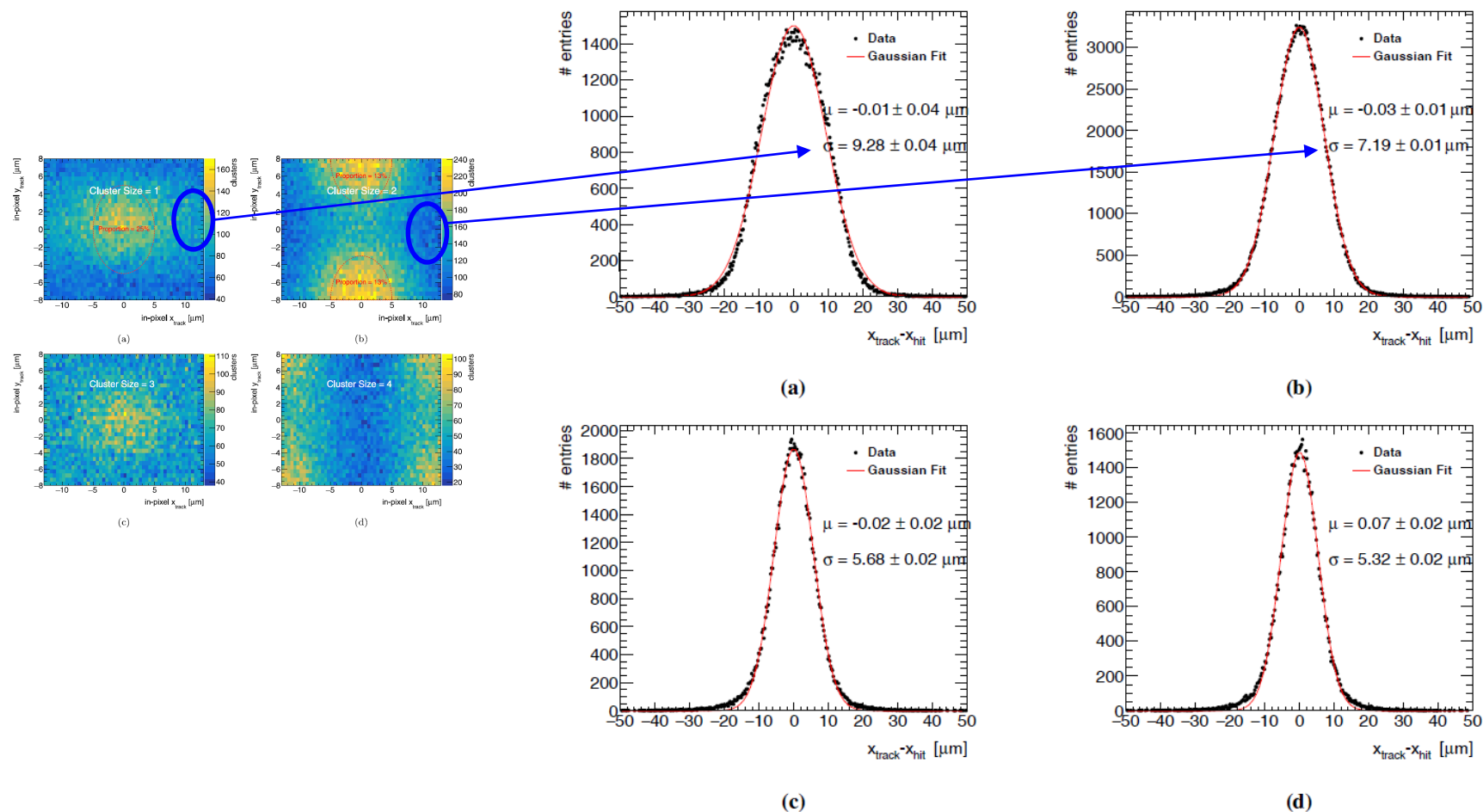


图 4.11 不同 cluster 大小在 x 方向上的残差分布: (a) cluster size = 1 (b) cluster size = 2 (c) cluster size = 3 (d) cluster size = 4。实验参数: 束流能量 = 5.8 GeV, 阈值 = 200 e^- 。

击中位置对残差的影响

Y方向的残差基本不受击中位置影响

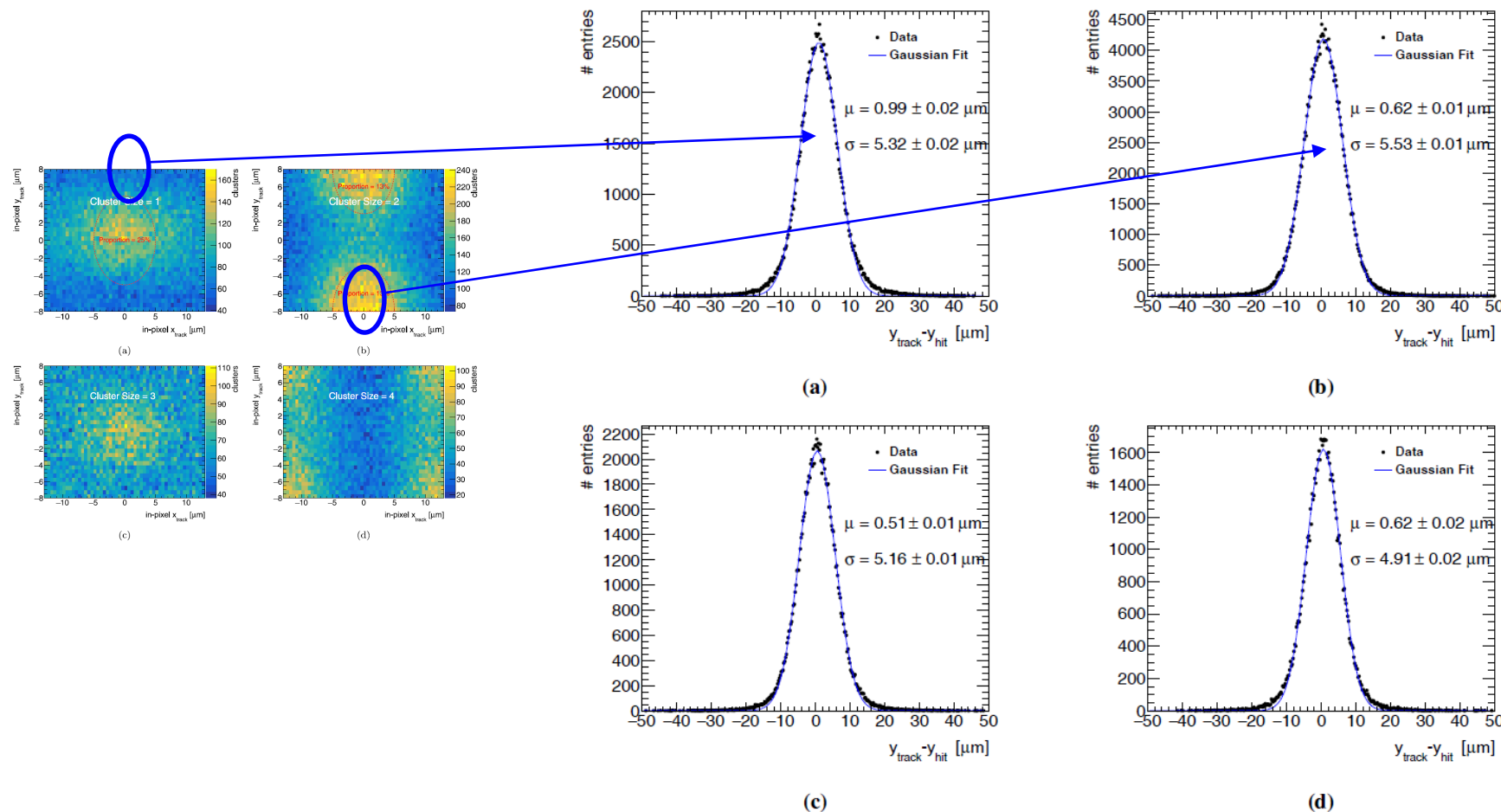


图 4.12 不同 cluster 大小在 y 方向上的残差分布: (a) cluster size = 1 (b) cluster size = 2 (c) cluster size = 3 (d) cluster size = 4。实验参数: 束流能量 = 5.8 GeV, 阈值 = 200 e^- 。

标称阈值下的探测效率

■ Track击中像素内不同位置的效率分布

- X方向的像素边缘出现效率损失

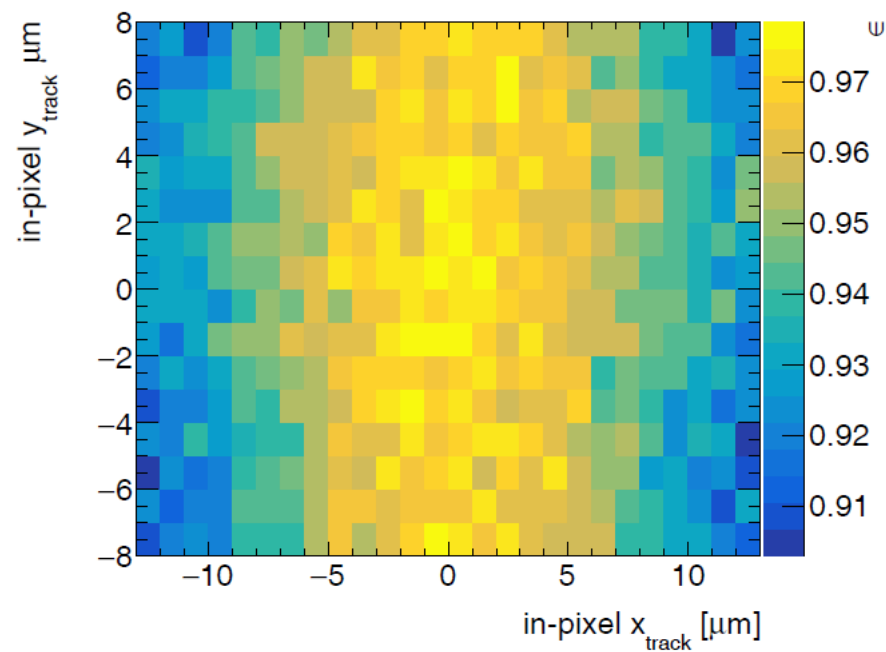


图 4.13 JadePix-3 探测效率。实验参数：束流能量 = 5.8 GeV，阈值 = 200 e^- 。位置符合范围
 $= 10 \times pitch / \sqrt{12}$ 。

阈值扫描

■ 降低阈值能够同时改善

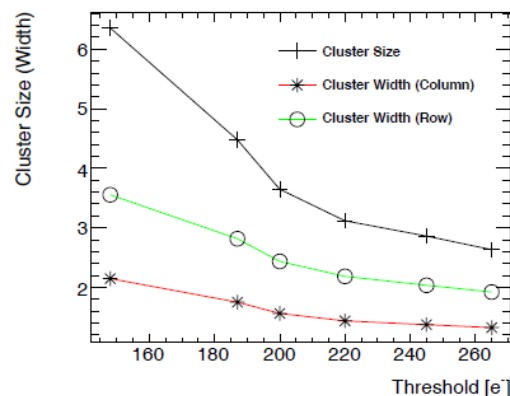
- X方向的效率损失
- X方向的分辨率

■ 最佳分辨率

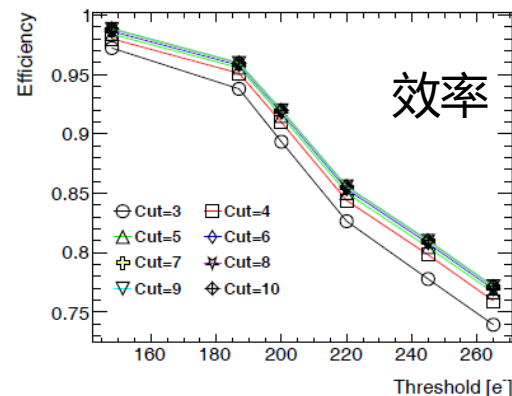
- X方向5.2
- Y方向4.6

■ 未扣除芯片厚度的影响

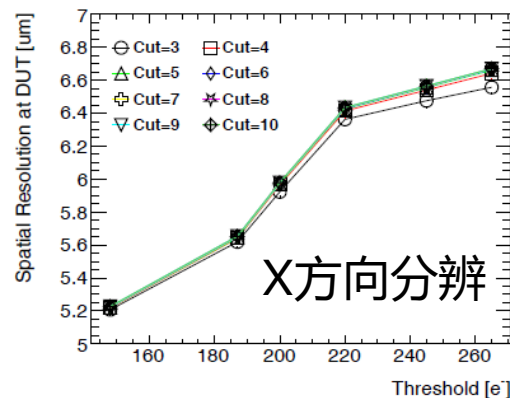
- 320 μm



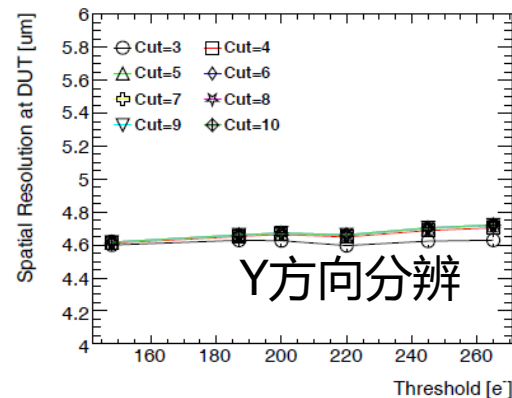
(a)



(b)



(c)



(d)

图 4.14 阈值扫描对 (a) 平均簇大小, (b) 效率, (c) x 方向分辨率, 以及 (d) y 方向分辨率的影响。实验参数: 束流能量 = 5.4 GeV, 阈值范围: 从 148 e^- 到 265 e^- 。

空间分辨率的问题在哪里？

■ 设计？

- 16um x 23.1um pitch已经是同类芯片中最小的
- TCAD仿真验证了空间分辨率的可行性
- 所有的电路功能和性能都通过了测试验证

■ 测试？

- 激光测试从微观层面验证了3um空间分辨率的可行性
- 束流测试从系统软硬件集成到数据分析由董胜包办，科大陈智良参加了数据分析

讨论

- 3 um空间分辨率的目标如何完成
- TJ180的流片渠道
 - 法国IPHC: MPW单位面积约20-30万, 工程批大概240-260万
 - 上海TJ办公室: MPW单位面积约100万, 工程批约400万
 - 西班牙IFAE: 与IPHC类似?