JadePix-3束流望远镜

研究进展和近期测试结果

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第三届半导体辐射探测器研讨会
April 12–16 2023

1. 中国科学院高能物理研究所 2. 中国科学与技术大学 3. 华中师范大学

内容

- JadePix-3芯片介绍
- JadePix-3束流望远镜研究进程
- 近期束流测试结果

时间线

芯片基本功能测试：
阈值/噪声/功耗/…

单芯片测试

3层束流望远镜原型

宇宙线测试
多芯片同步读出系统

第一次束流测试 Nov. 2022@BSRF
集成离线分析分析软件Corryvreckan

第二次束流测试 Dec. 2022@
首次得到望远镜空间分辨以及JadePix-3空间分辨

4层束流望远镜原型

5层束流望远镜原型

第三次束流测试 April 2023@DESY
阈值扫描/Cluster Size/Spatial resolution/Efficiency/…
More analysis in progress

JadePix-3芯片设计

“Status report on MAPS in China”, 2021 CEPC workshop, Yunpeng Lu

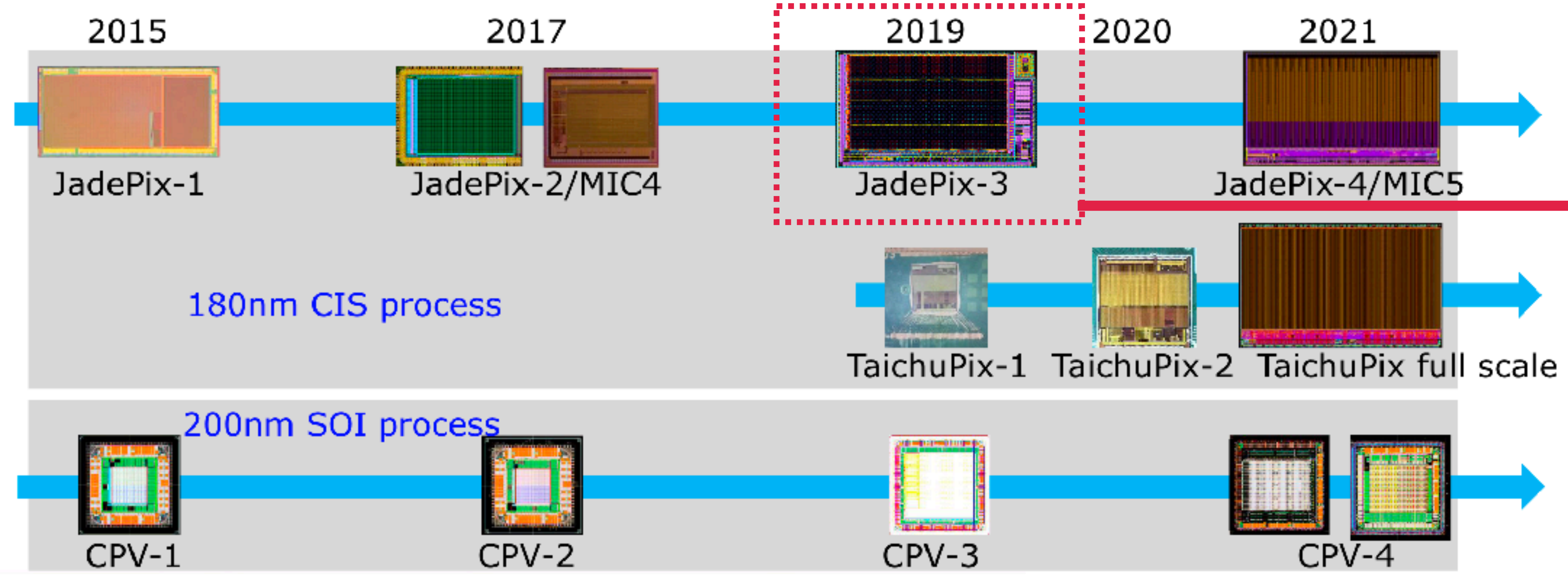


Fig.1 Roadmap of silicon pixel sensor for vertex detector in China.

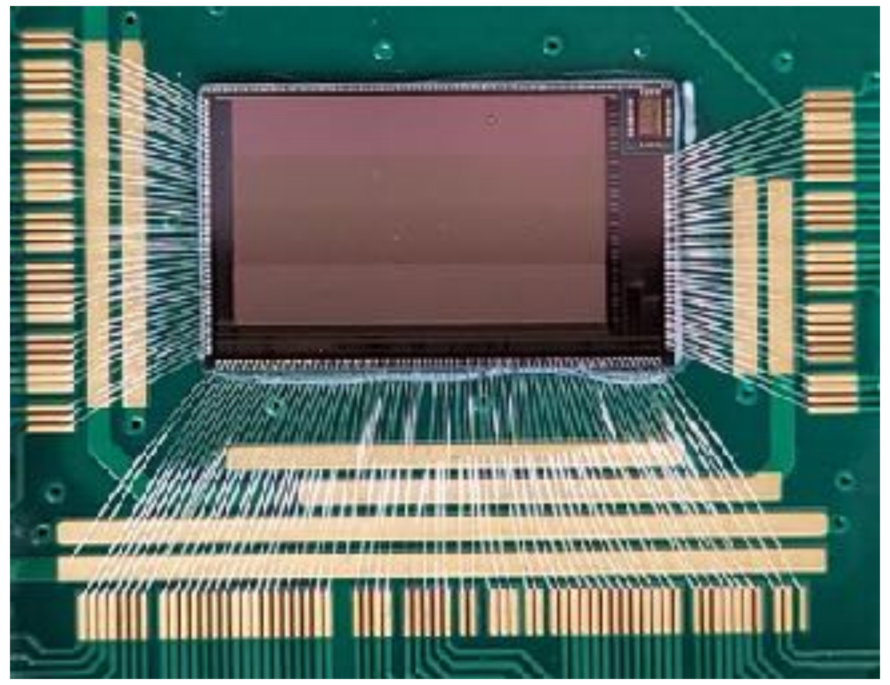


Fig.2 芯片绑定后照片

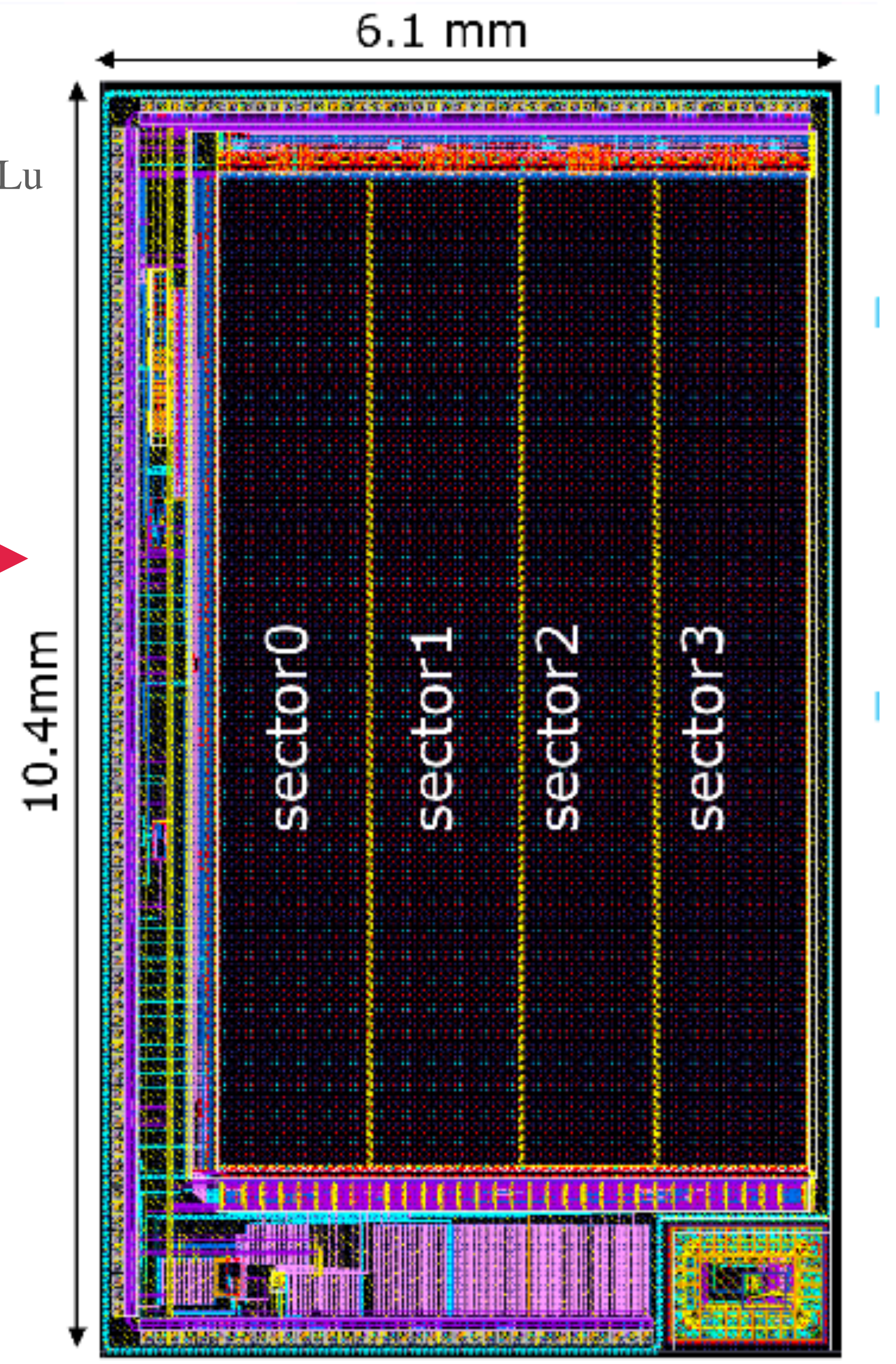


Fig.3 JadePix-3布局，4个平行扇区，可在行方向上扩展

JadePix-3是CEPC顶点探测器原型之一。

设计目标是高分辨率、低功耗和快速读出。

采用TowerJazz 180nm CMOS技术生产。

设计了4个部分来研究不同的模拟前端和数字电路。(见表1)

芯片面积：$10.4mm(row) \times 6.1mm(col)$

像素阵列: $512(row) \times 192(col)$

最小像素尺寸: $16um \times 23.11um$

Tabel. 1 The matrix design of JadePix-3

Sector	Diode	Analog	Digital	Pixel Size
0	2+2 um	FE_V0	DGT_V0	16 x 26 um^2
1	2+2 um	FE_V0	DGT_V1	16 x 26 um^2
2	2+2 um	FE_V0	DGT_V2	16 x 23.11 um^2
3	2+2 um	FE_V1	DGT_V0	16 x 26 um^2

Single Sensor Test

- 基于分布式控制系统框架IPBus来开发单芯片测试系统，IPbus具有扩展性，可以方便扩展到未来的多芯片读出
- 测试方法： 电脉冲测试，红外线激光束测试，放射源（90Sr）测试。
- 测试结果摘要：
  - 最小阈值： $90e^-$ – $140e^-$
  - 噪声： 低于1×10^{-10}/帧/像素
  - 功耗： 127 mW
  - 空间分辨率：达到3um(红外线激光束测试)
- Publication: Design and Characterization of the JadePix-3 CMOS pixel sensor
  https://doi.org/10.1016/j.nima.2022.167967

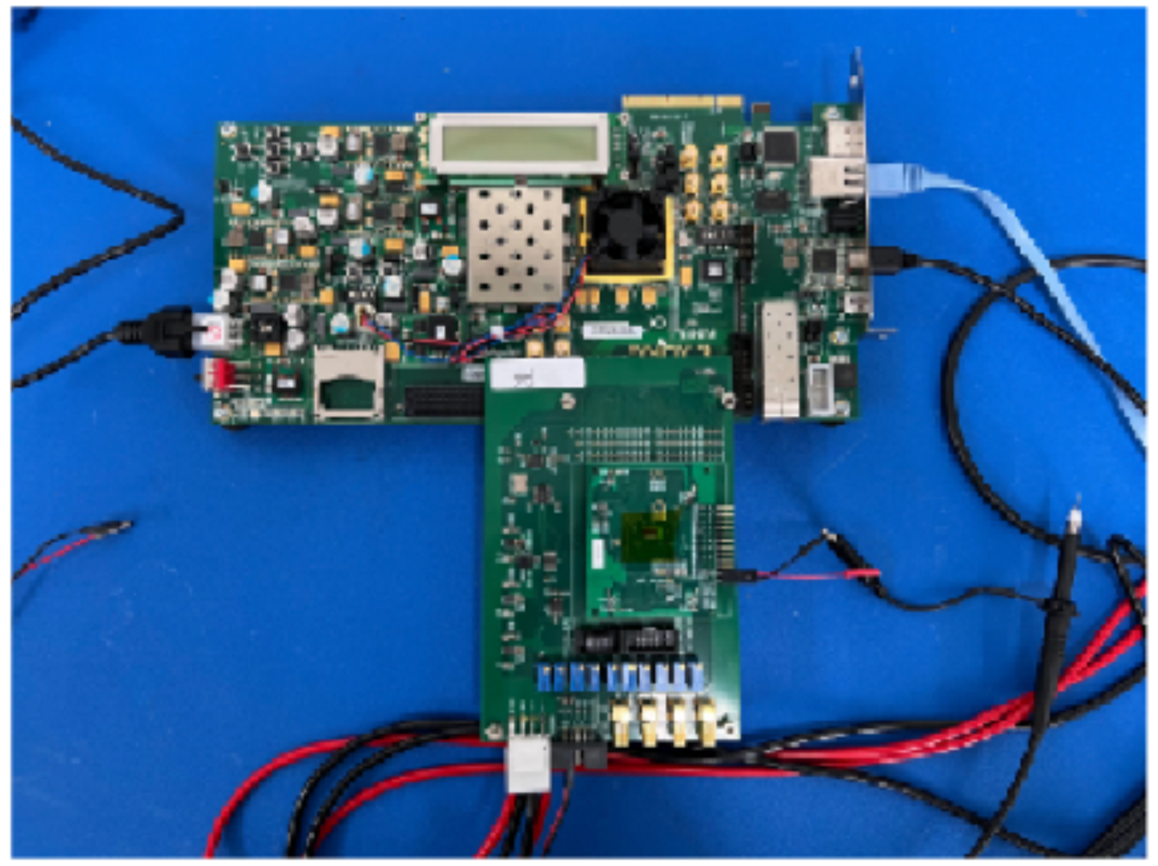


Fig.1 单芯片测试系统

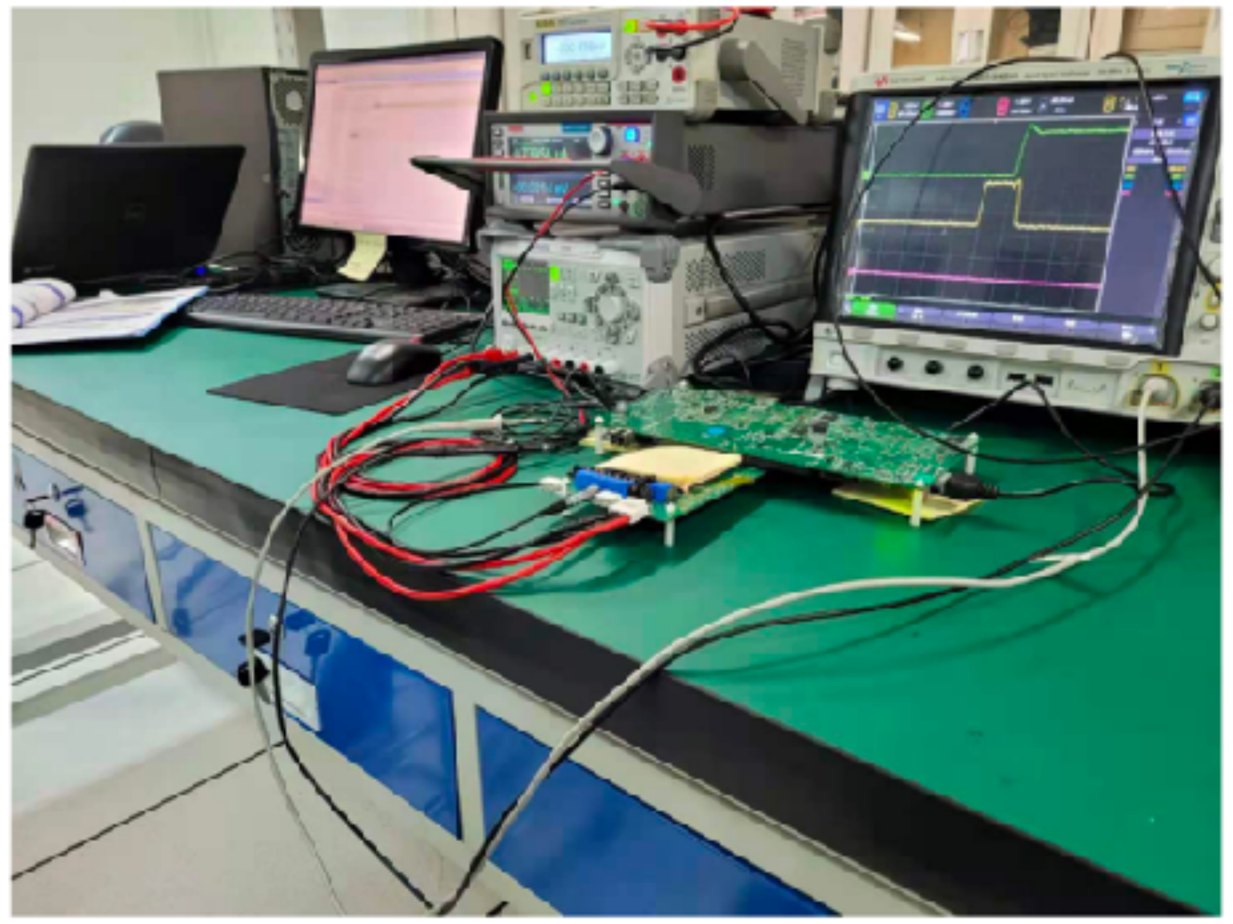


Fig.2 单芯片测试系统@CCNU

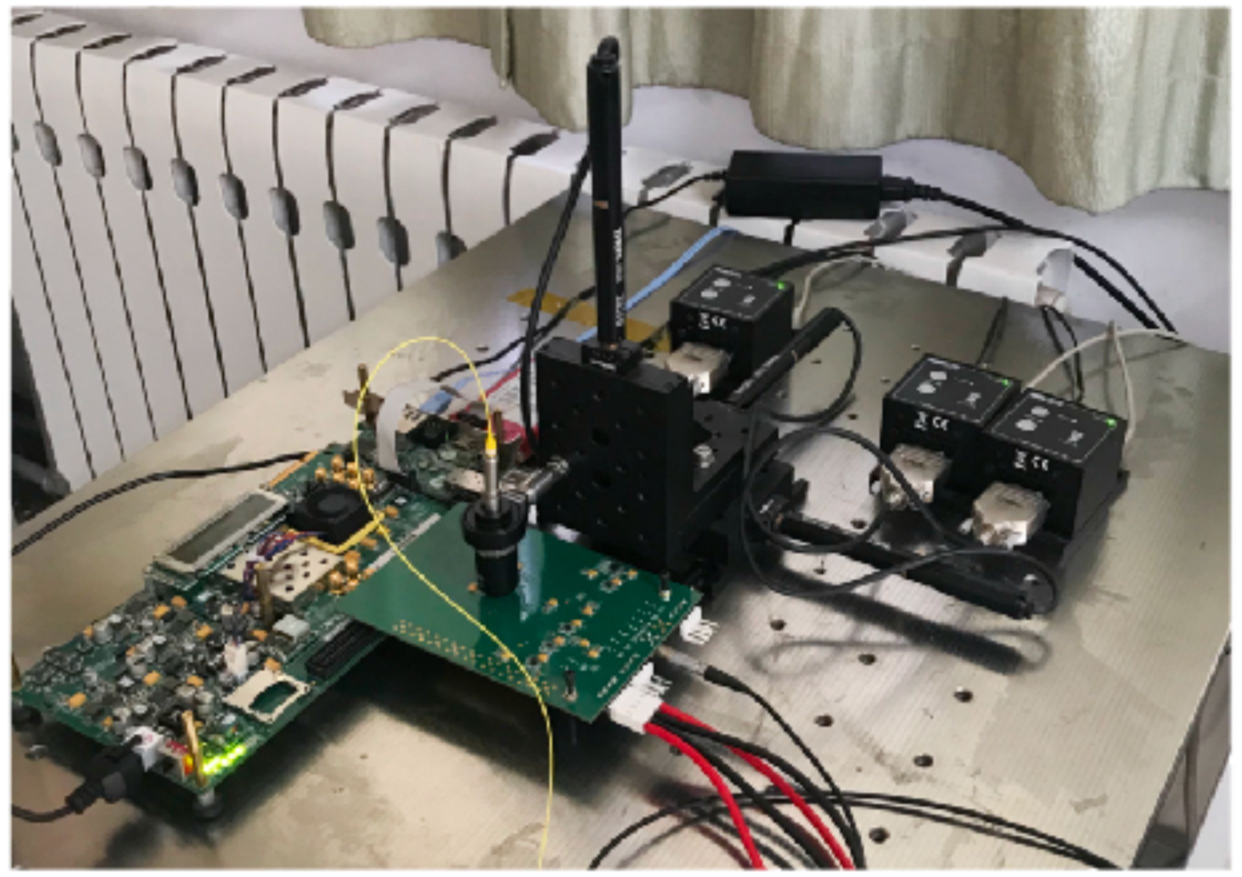


Fig.3 红外激光测试平台

束流望远镜研究

- 设计通用多芯片同步读出系统，为了后续芯片验证做准备（JadePix-4/CPV4-3D）
- 掌握束流望远镜离线分析算法（径迹重建）
- 芯片设计迭代

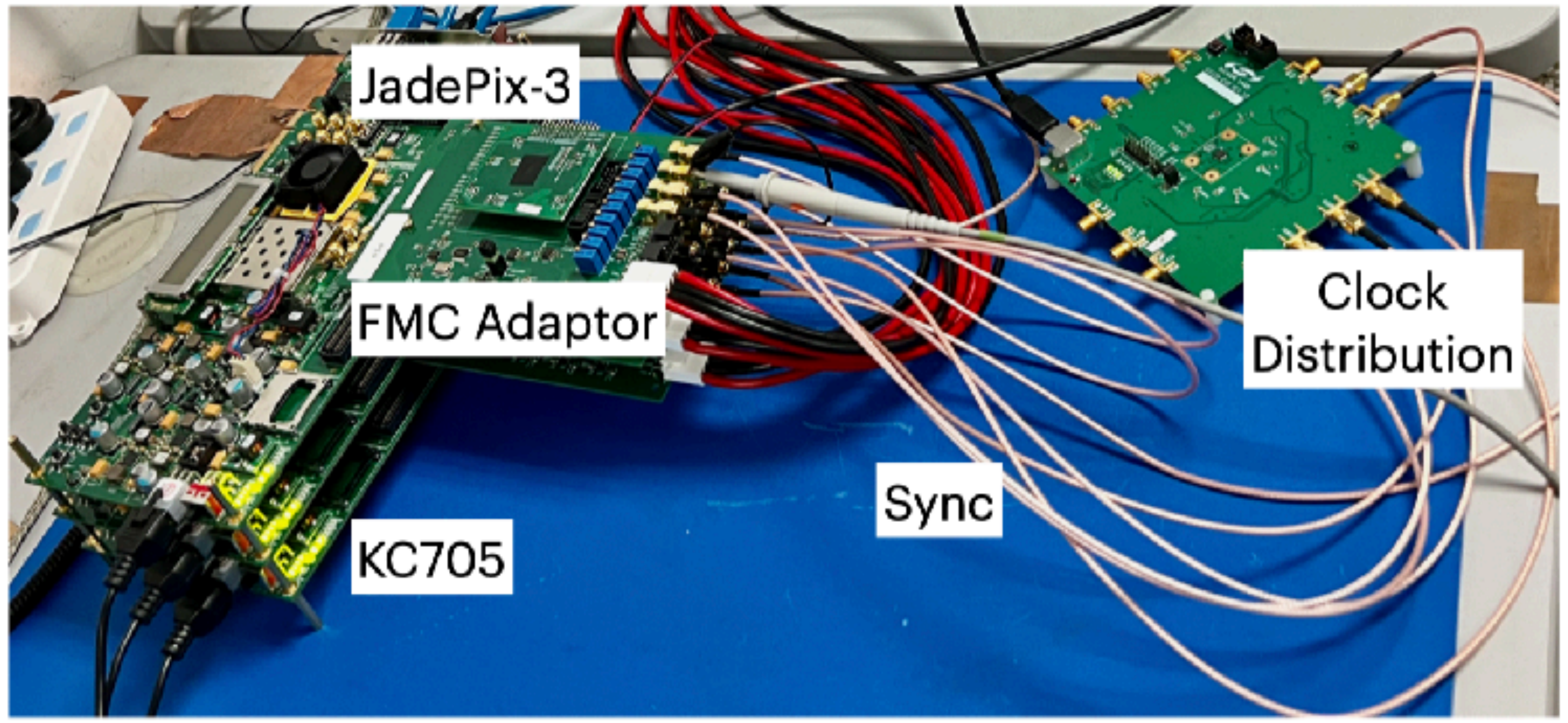


Fig.1 3层束流望远镜原型

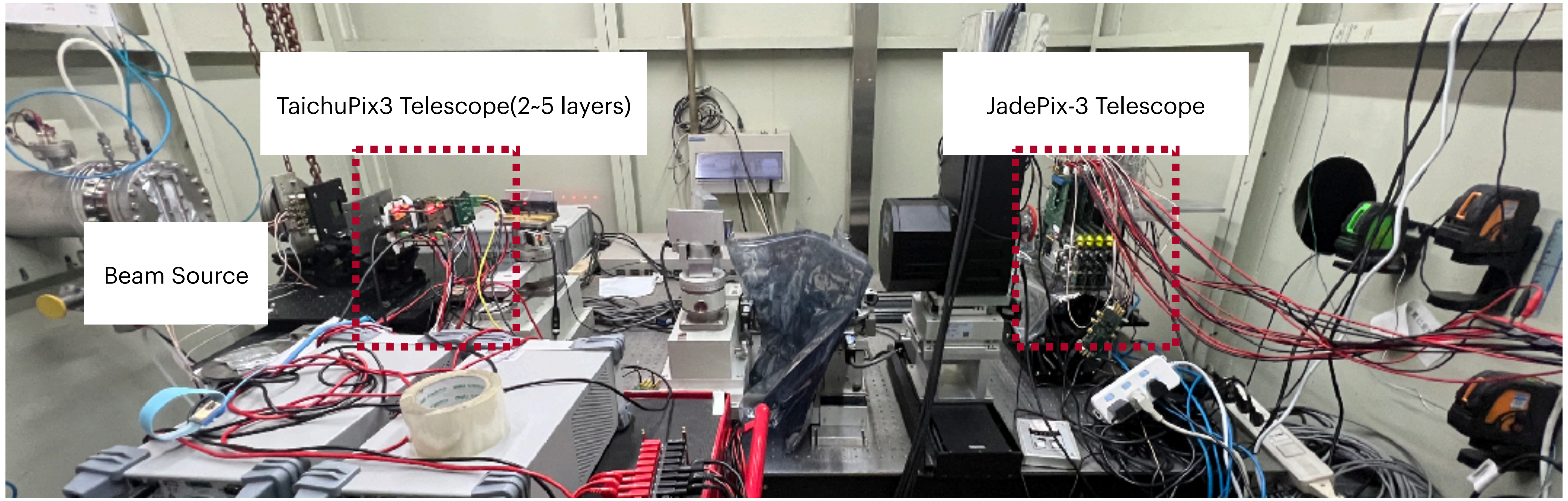
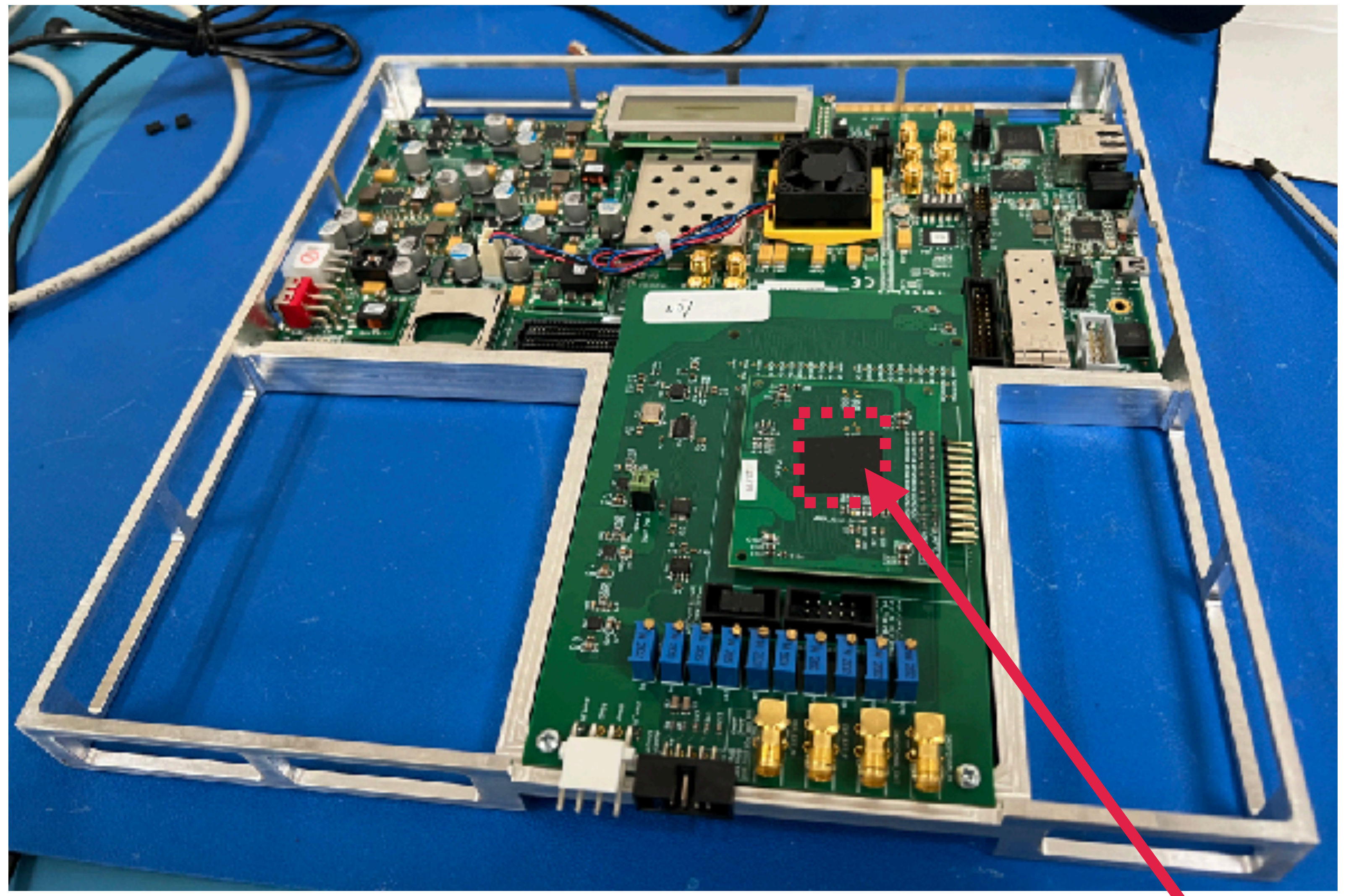


Fig2. 北京同步辐射首次束流测试

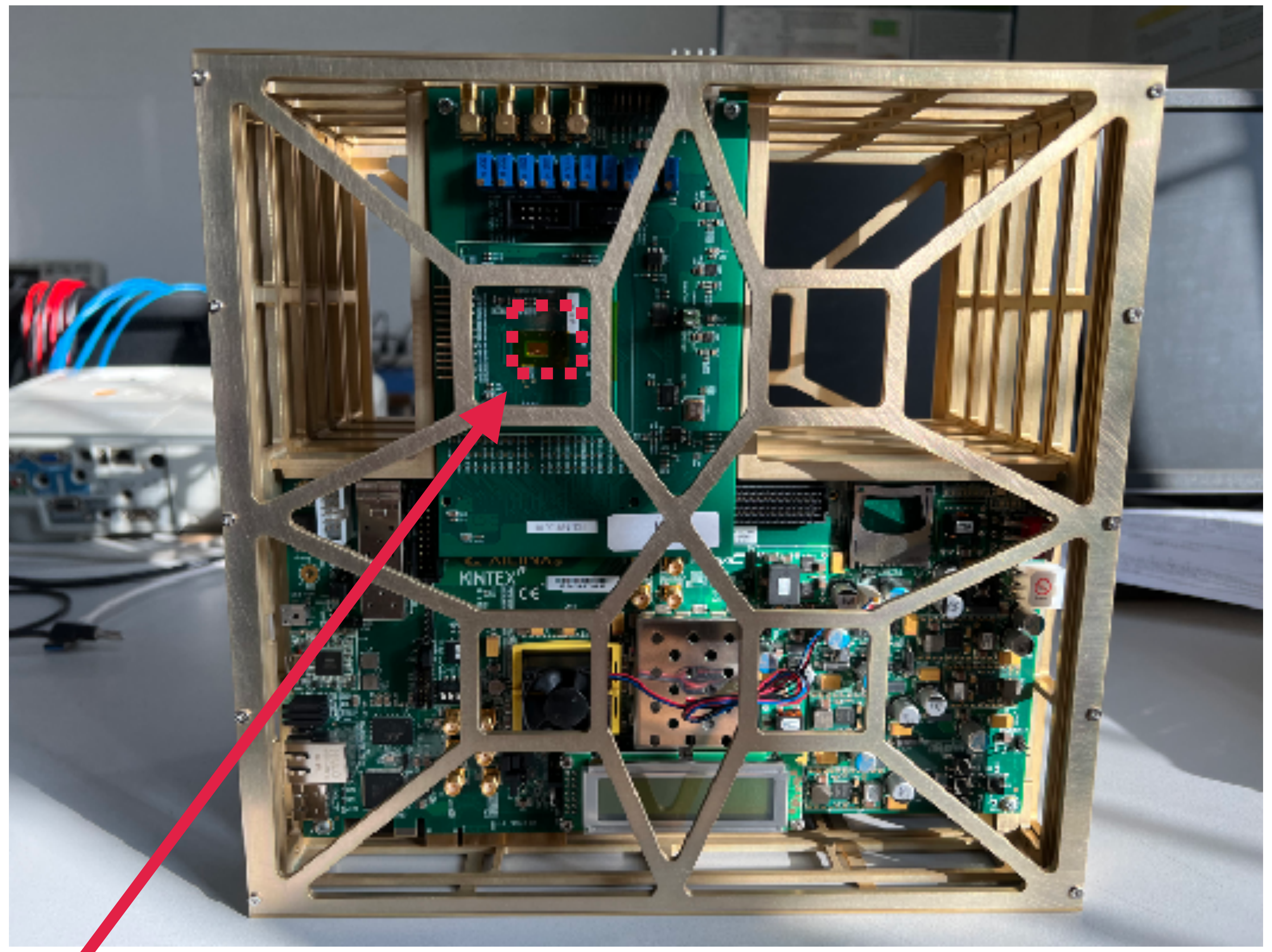
测试捕捉了几十条宇宙线，验证了多芯片同步读出系统设计

捕捉到15000条轨迹（0.1Hz/cm2）
Corryvreckan首次被用于离线数据分析

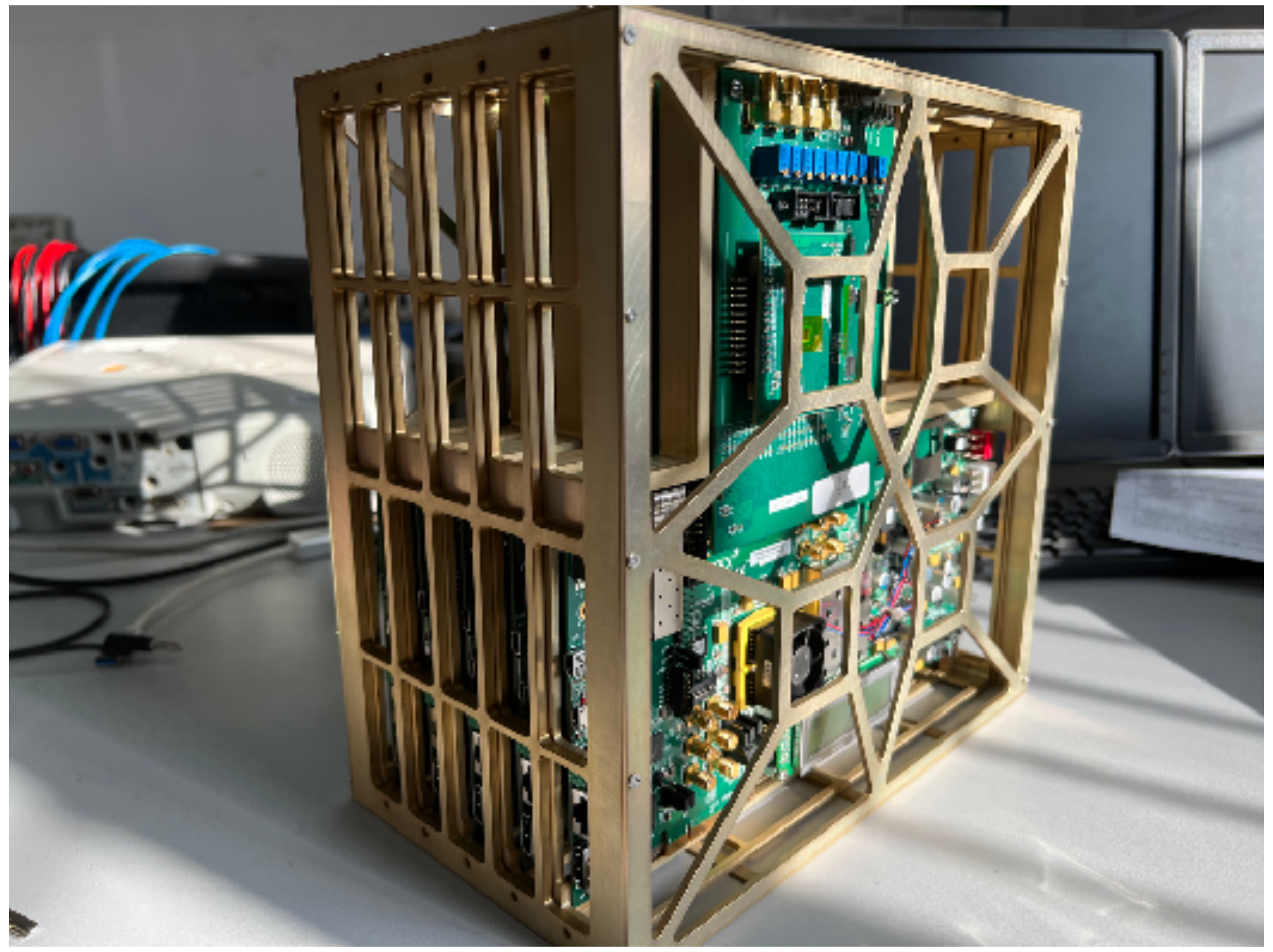
5层束流望远镜框架



Signal plane structure



Front view

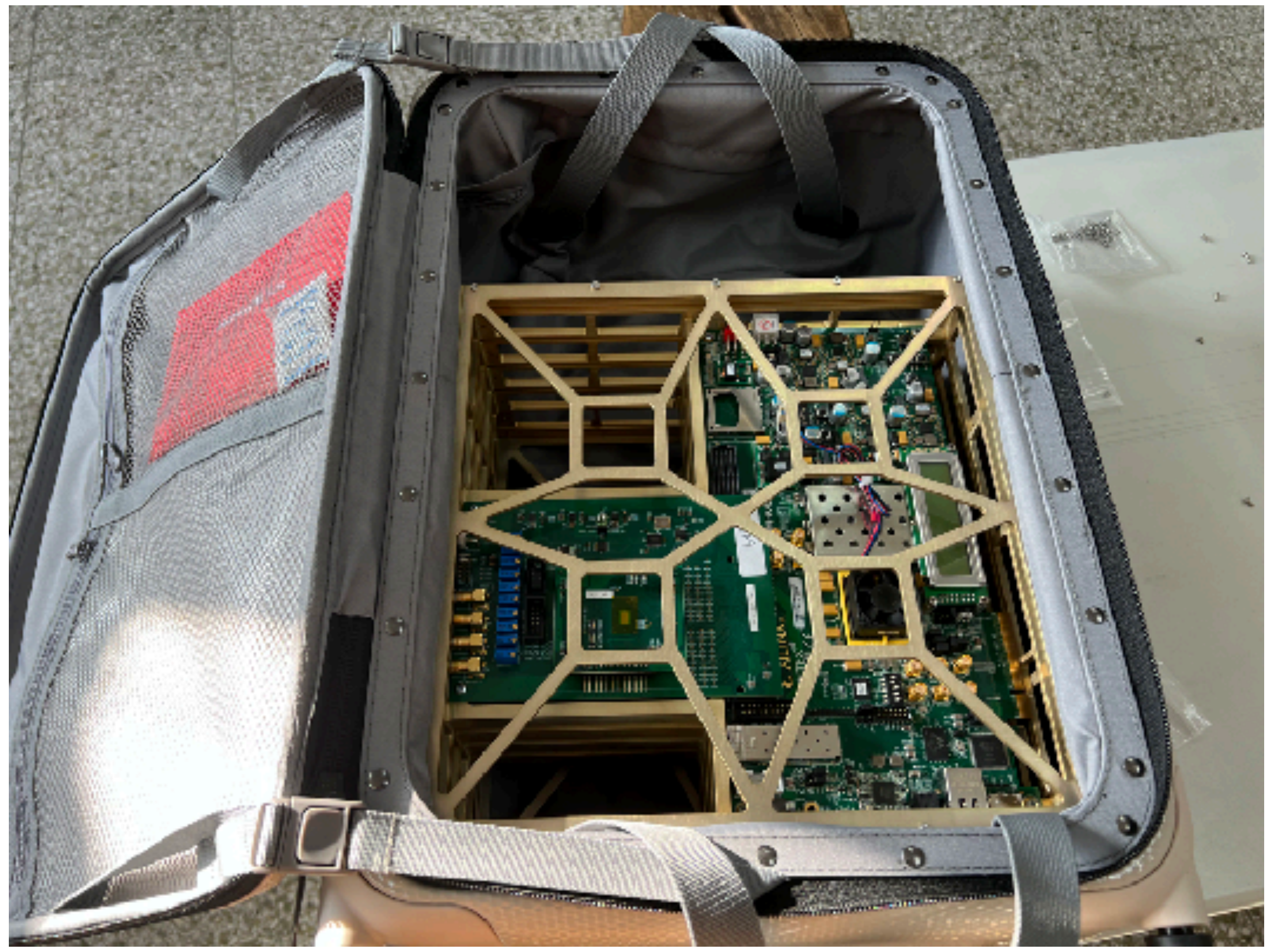


Side view

Sensor

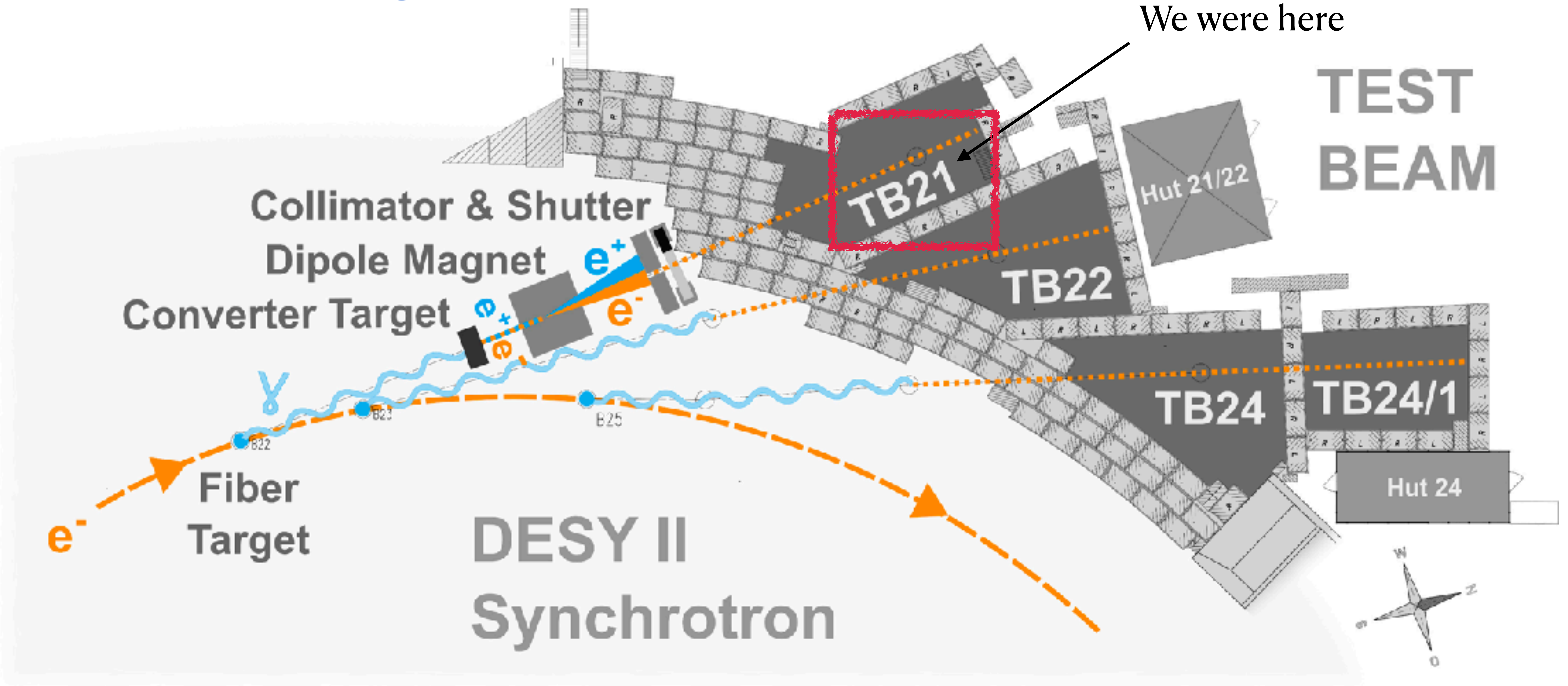
设计了稳定、易安装的望远镜保护框架

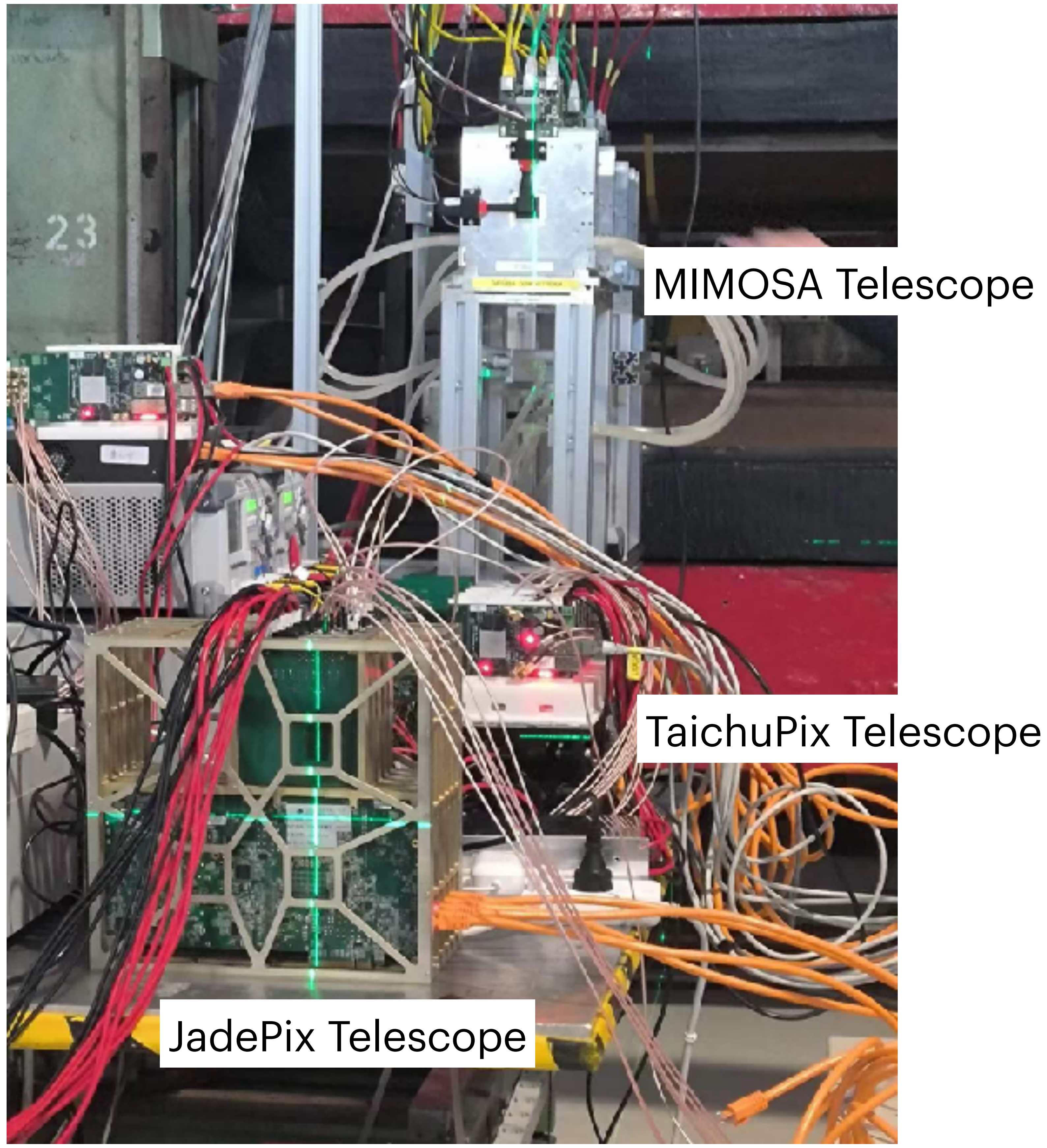
最多可安装5层望远镜系统



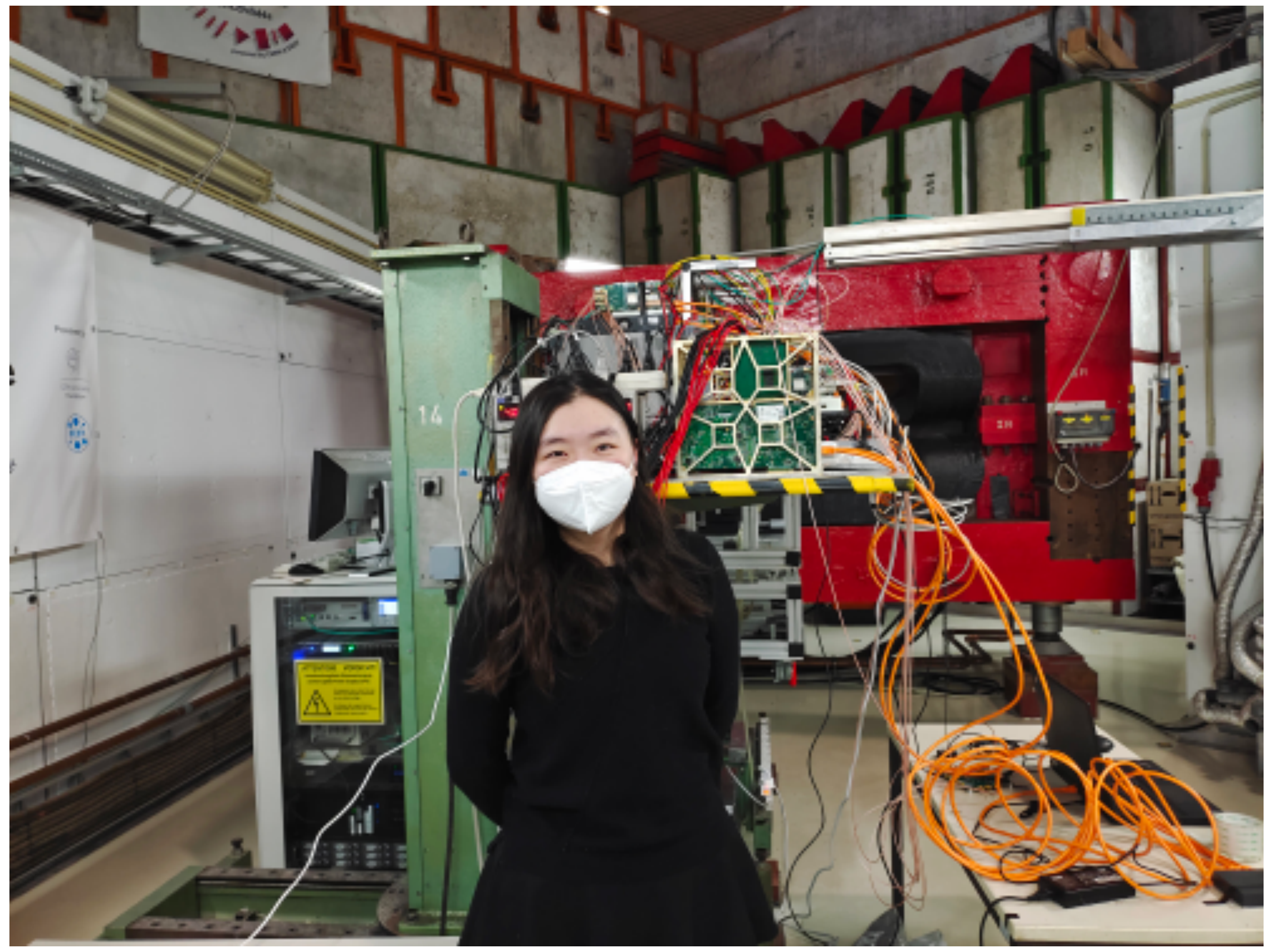
Good for transportation

束流测试@DESY TB21





Test Setup @DESY Dec.2022

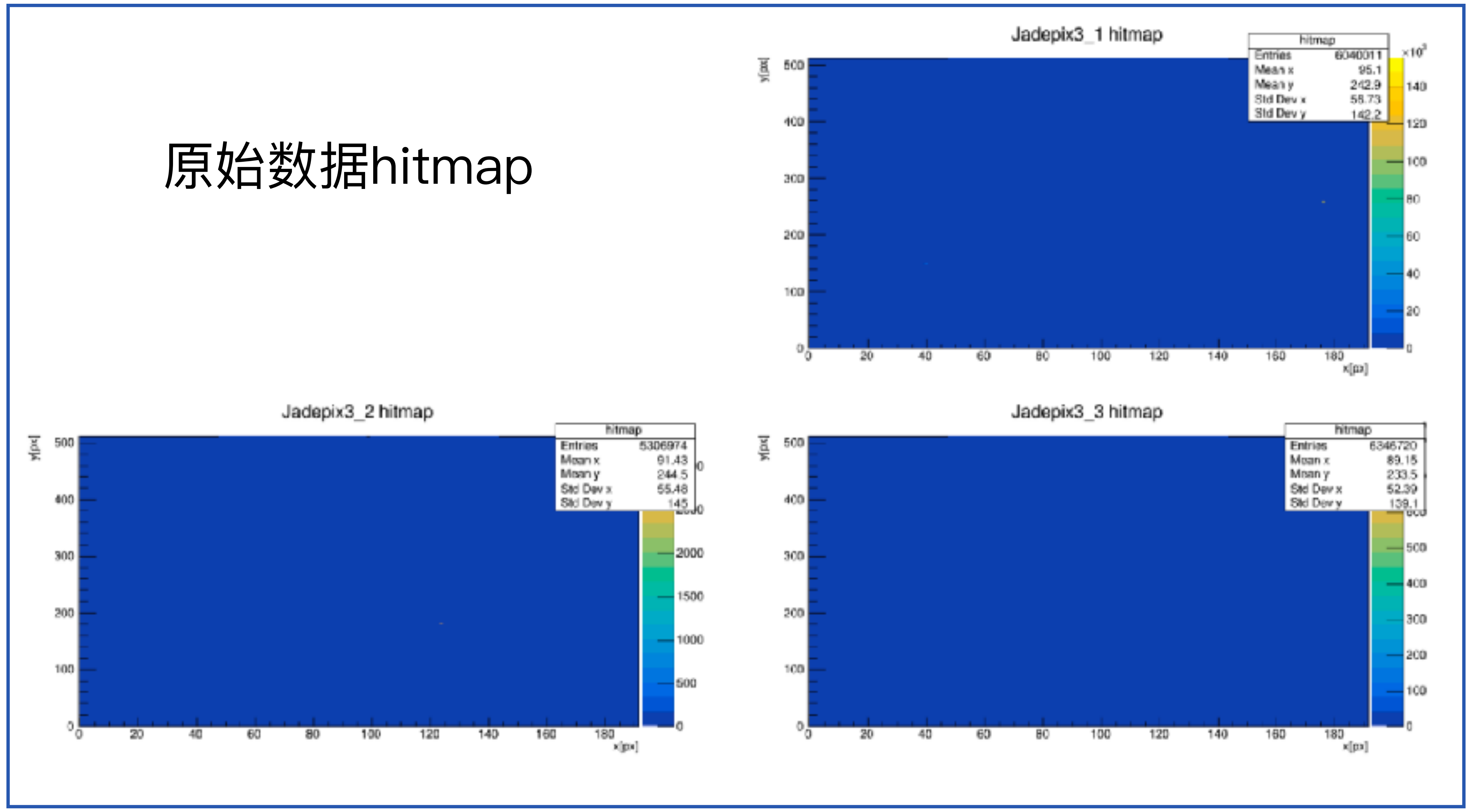


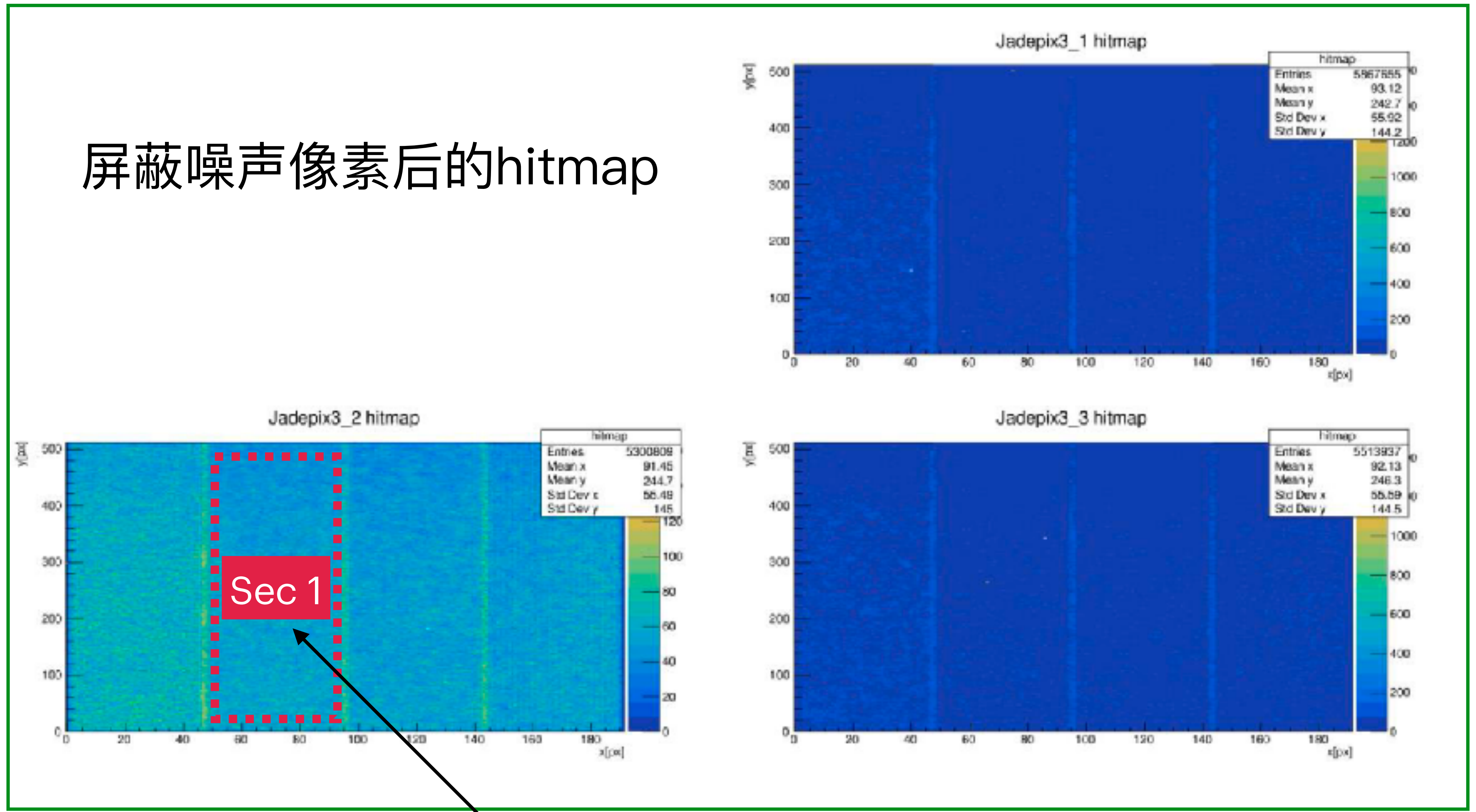
- The electron or positron beams are converted bremsstrahlung beams from carbon fibre targets in the electron–positron synchrotron DESY II.
- up to 1000 particles per cm^2 and energies from 1 to 6 GeV, an energy spread of ~5% and a divergence of ~1 mrad.
- 5 层MIMOSA26束流望远镜
- 6层TaichuPix–3束流望远镜
- 4层JadePix–3束流望远镜
- 大部分实验时间束流能量为4GeV

噪声像素和HitMap

- 每层芯片噪声像素2–3个

```
plane1 [41, 150] 1.0
plane1 [177, 259] 1.0
plane2 [38, 4] 1.0
plane2 [125, 183] 1.0
plane3 [70, 145] 1.0
plane3 [87, 343] 1.0
plane3 [100, 404] 1.0
```



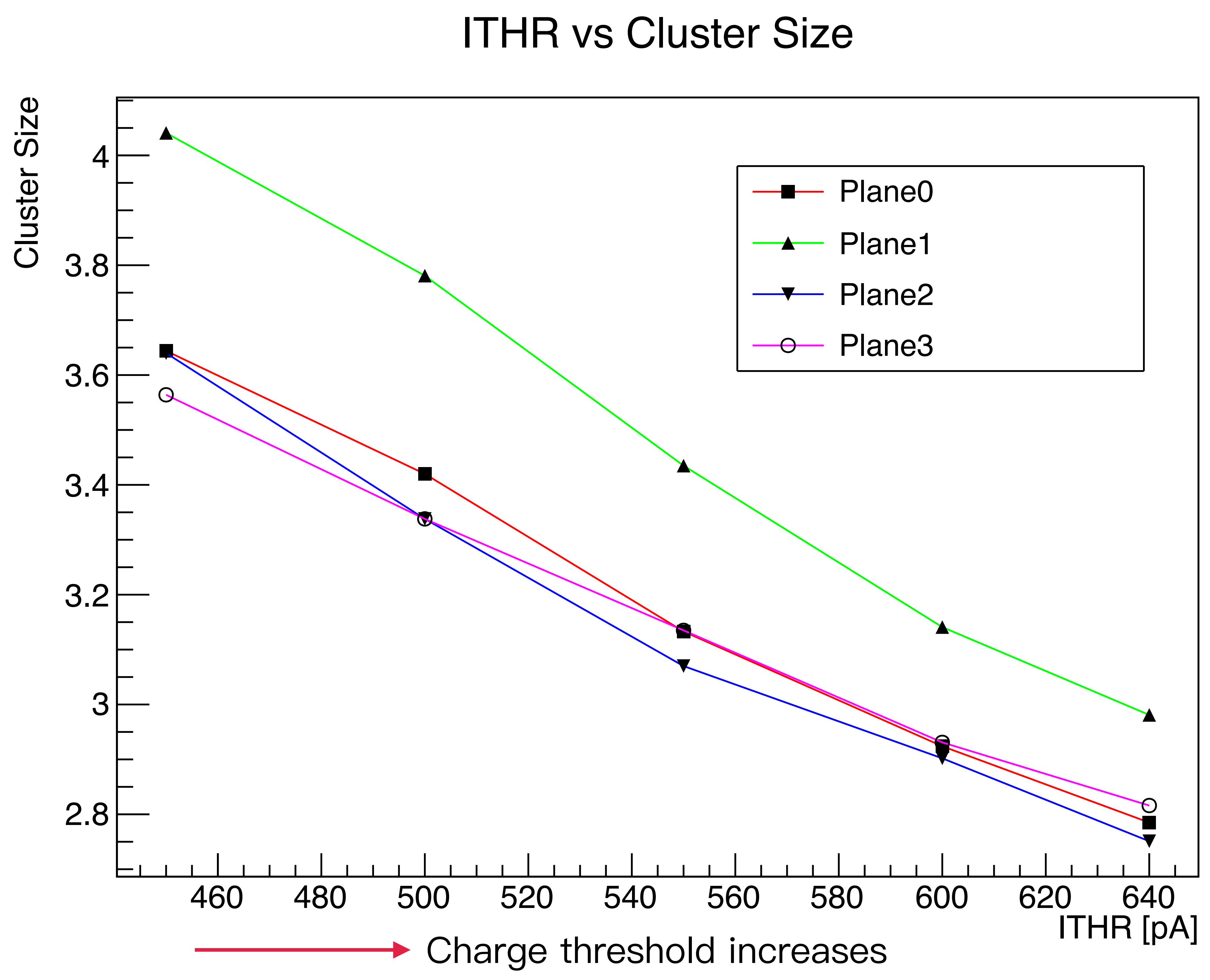


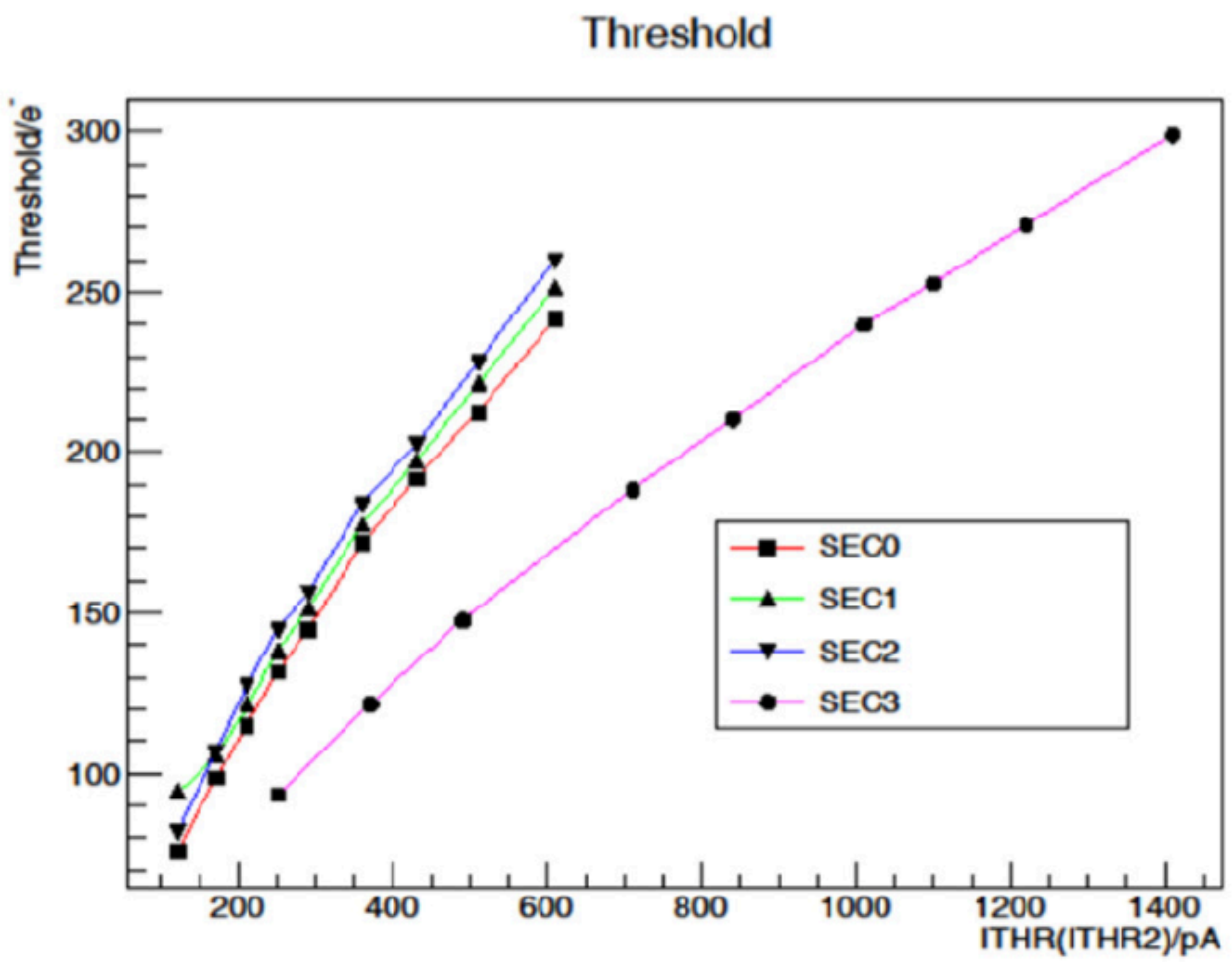
The region of interest (**ROI**)

- 为了降低数据分析的复杂性，选择Sector 1作为初步数据分析的区域，可以屏蔽Sector边界和Sector 2的不同像素尺寸的影响

Cluster Size

通过片内DAC调节阈值电流（ITHR），测试范围460pA–640pA，等效阈值电荷～200e⁻ – ～250e⁻



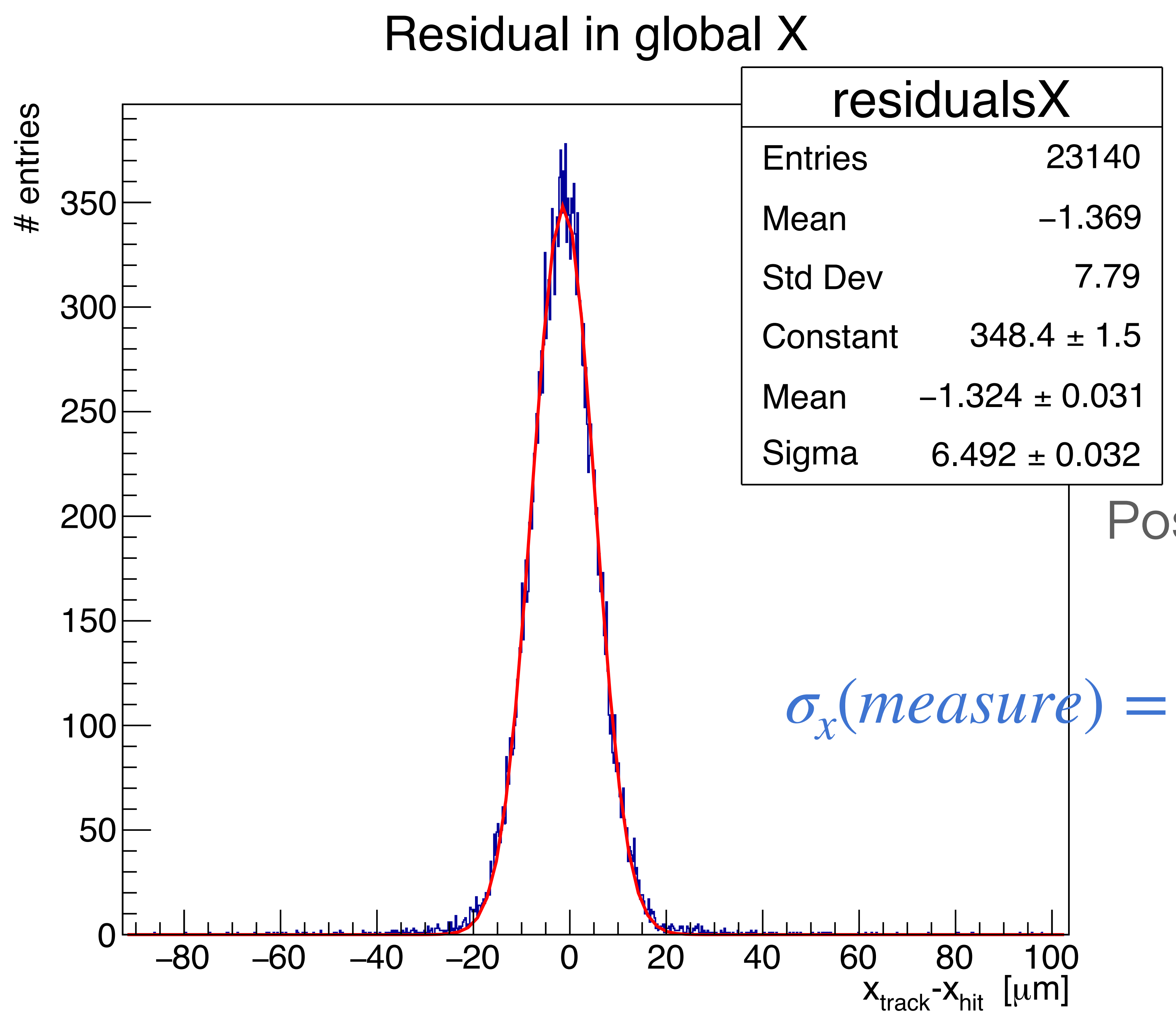


~200e-

~250e-

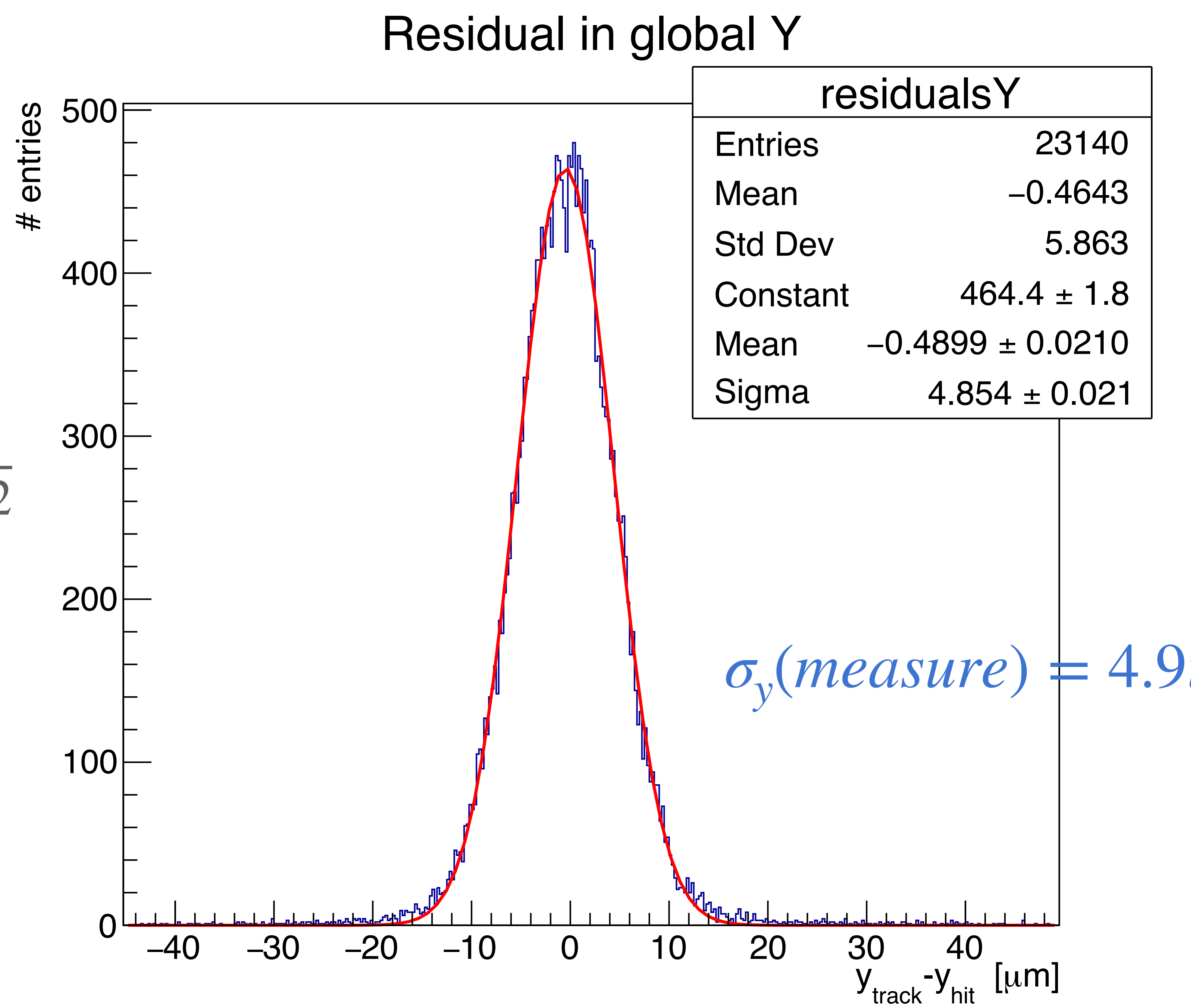
随着ITHR的增加（电荷阈值增加）：Cluster Size大小从3.6降至2.8（Plane 0/2/3

测量位置残差



Position cut: $20 \times pitch/\sqrt{12}$

$\sigma_x(measure) = 6.5um$



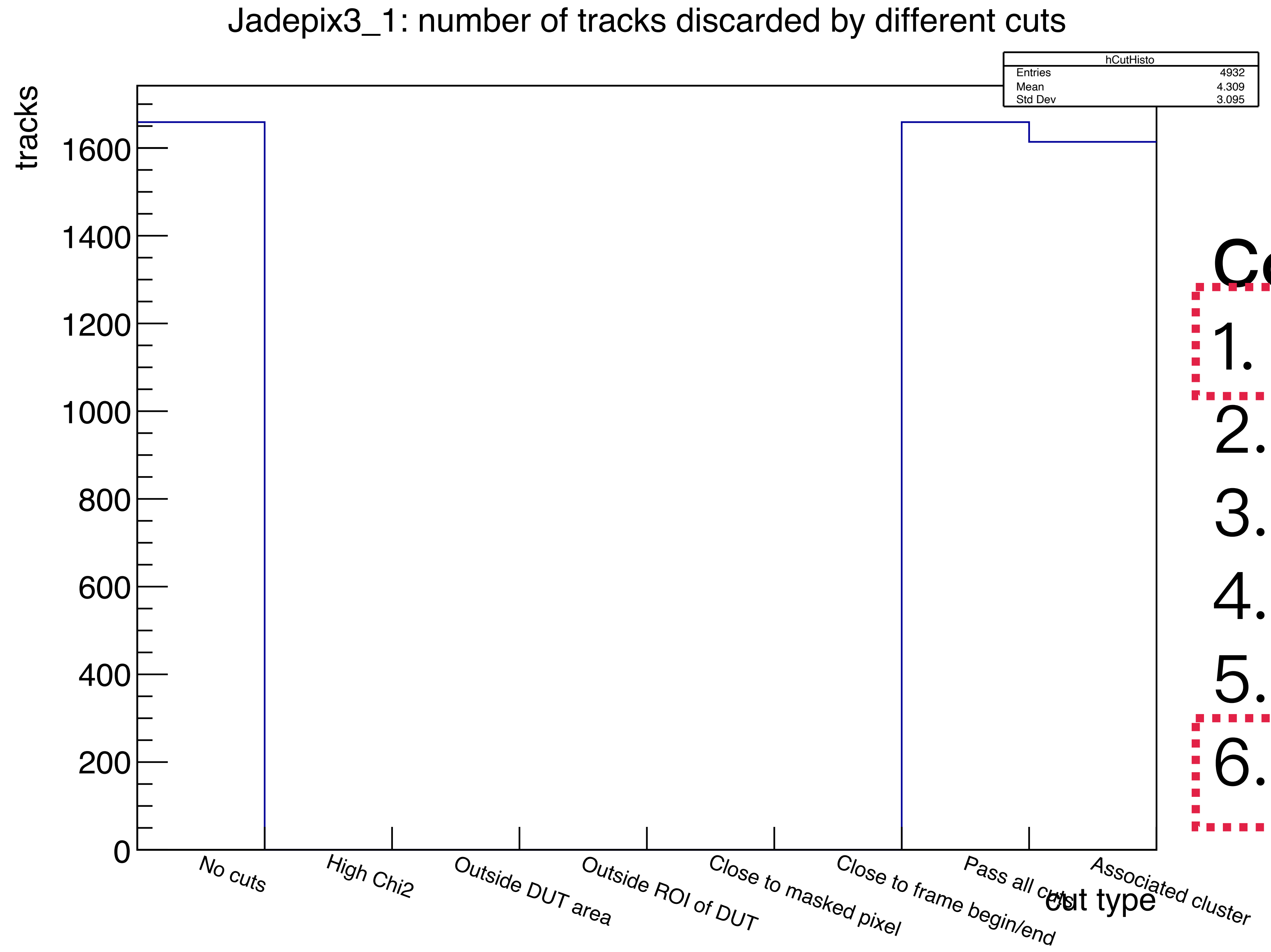
$\sigma_y(measure) = 4.9um$

1. X、Y方向测量残差sigma分别为6.5um、4.9um
2. $\sigma^2_{meas} = \sigma^2_{DUT} + \sigma^2_{tel}$
3. 若每层望远镜的空间分辨相同： $\sigma^2_{meas} = k\sigma^2_{plane}$ ， $k = \dfrac{\sum_i^N z_i^2}{N\sum_i^N z_i^2 - (\sum_i^N z_i)^2}$

$N = 3,\ k = \dfrac{3}{7}$ $\quad \sigma_x(tel) = 3.5\ um, \sigma_y(tel) = 2.7\ um$ $\quad \sigma_x(DUT) = 5.4\ um, \sigma_y(DUT) = 4.1\ um$

探测效率

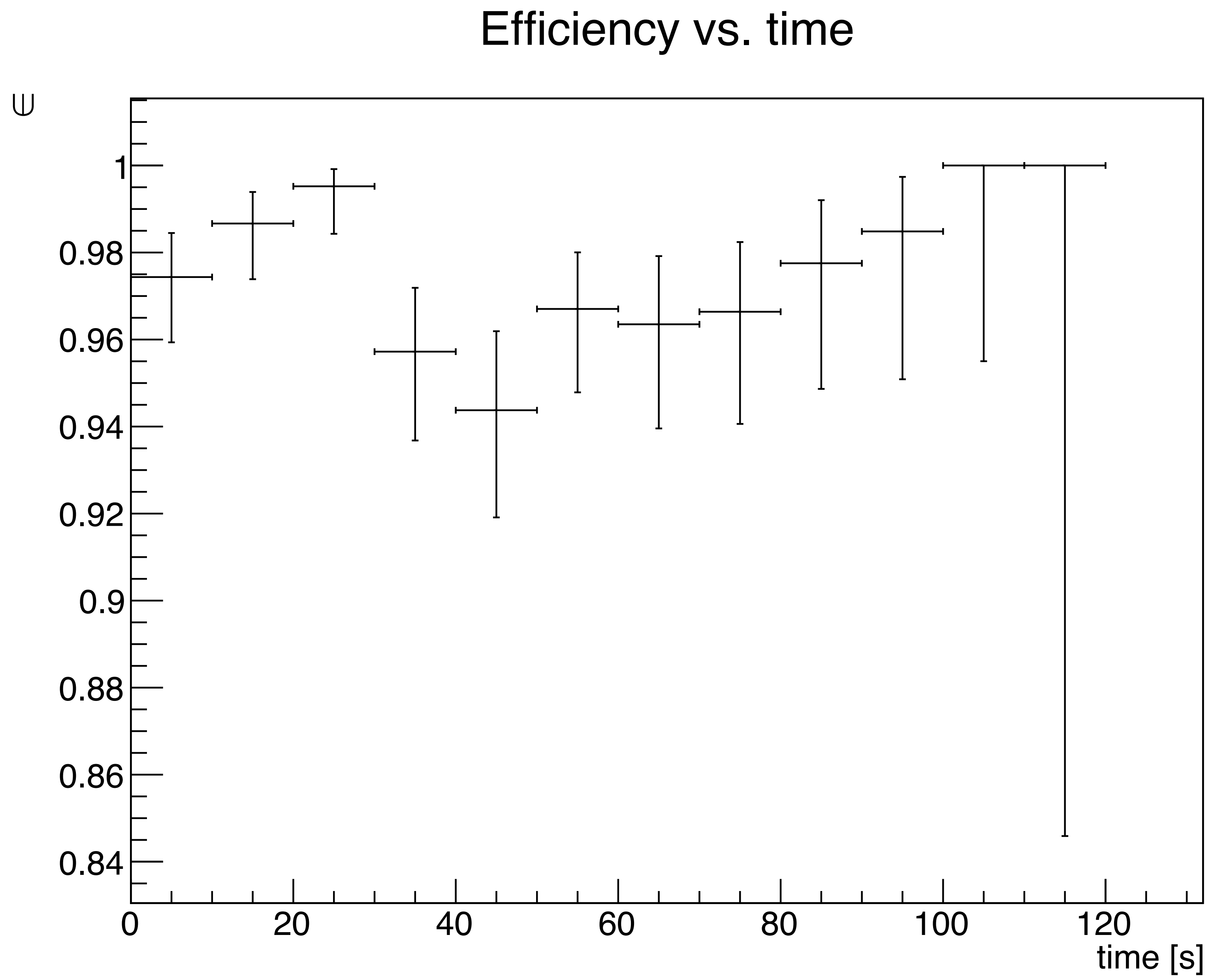
$$Total\ Efficiency = \frac{Number\ of\ Tracks\ which\ meet\ criteria}{Number\ of\ Total\ Tracks}$$



Conditions for Track deselection:

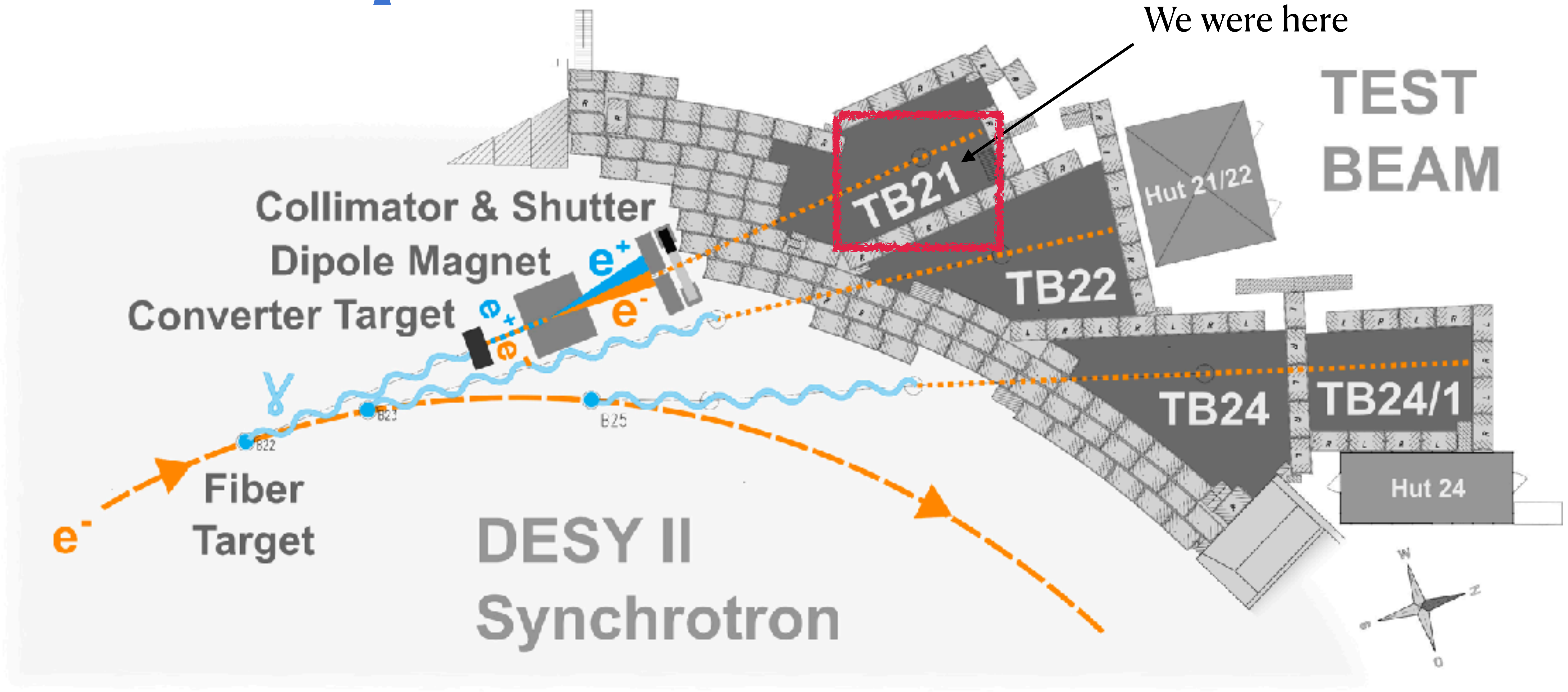
1. High Chi2
2. Outside DUT area
3. Outside ROI of DUT
4. Close to masked pixel
5. Close to frame edge
6. DUT association cut

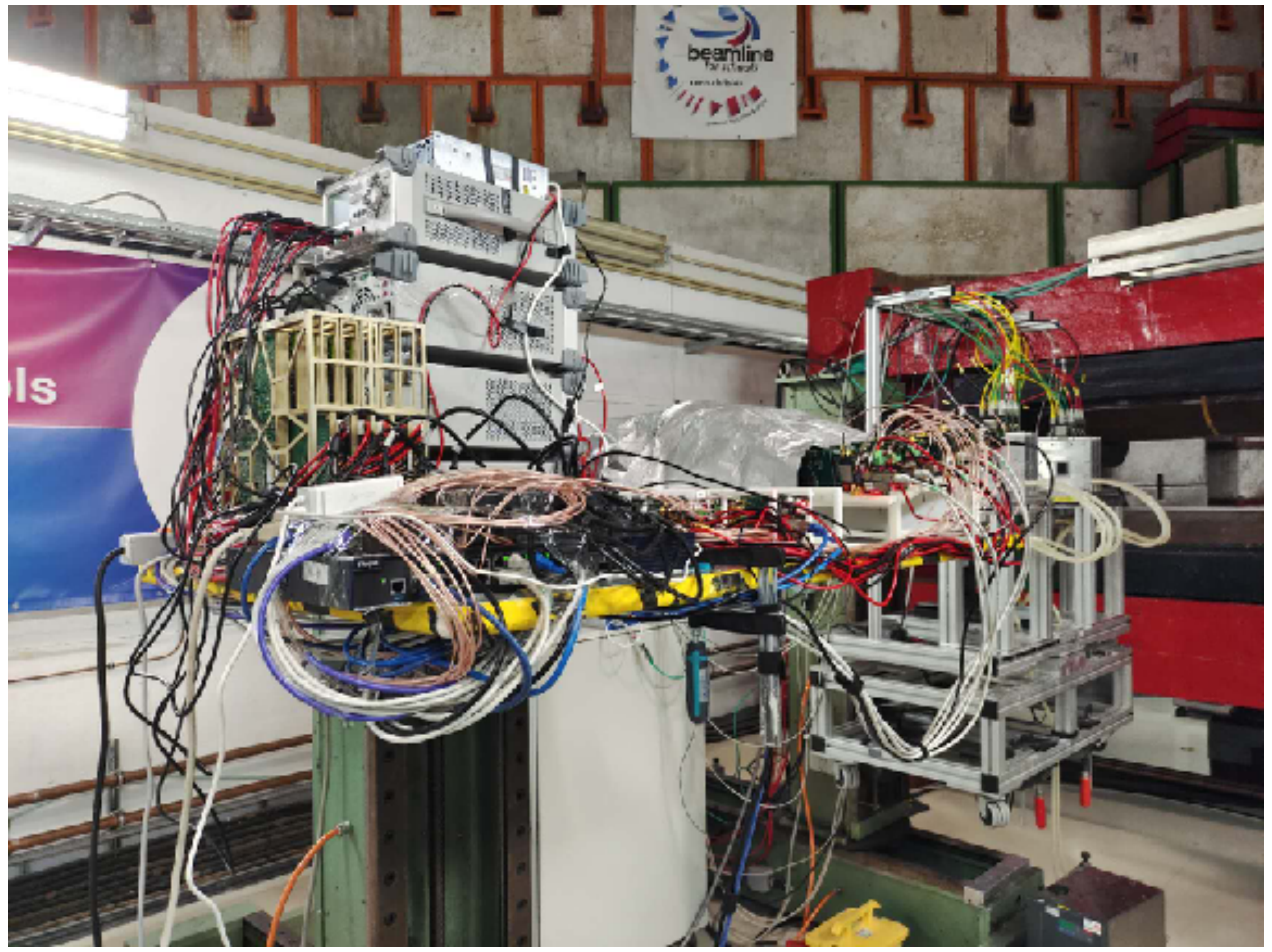
Now adopted



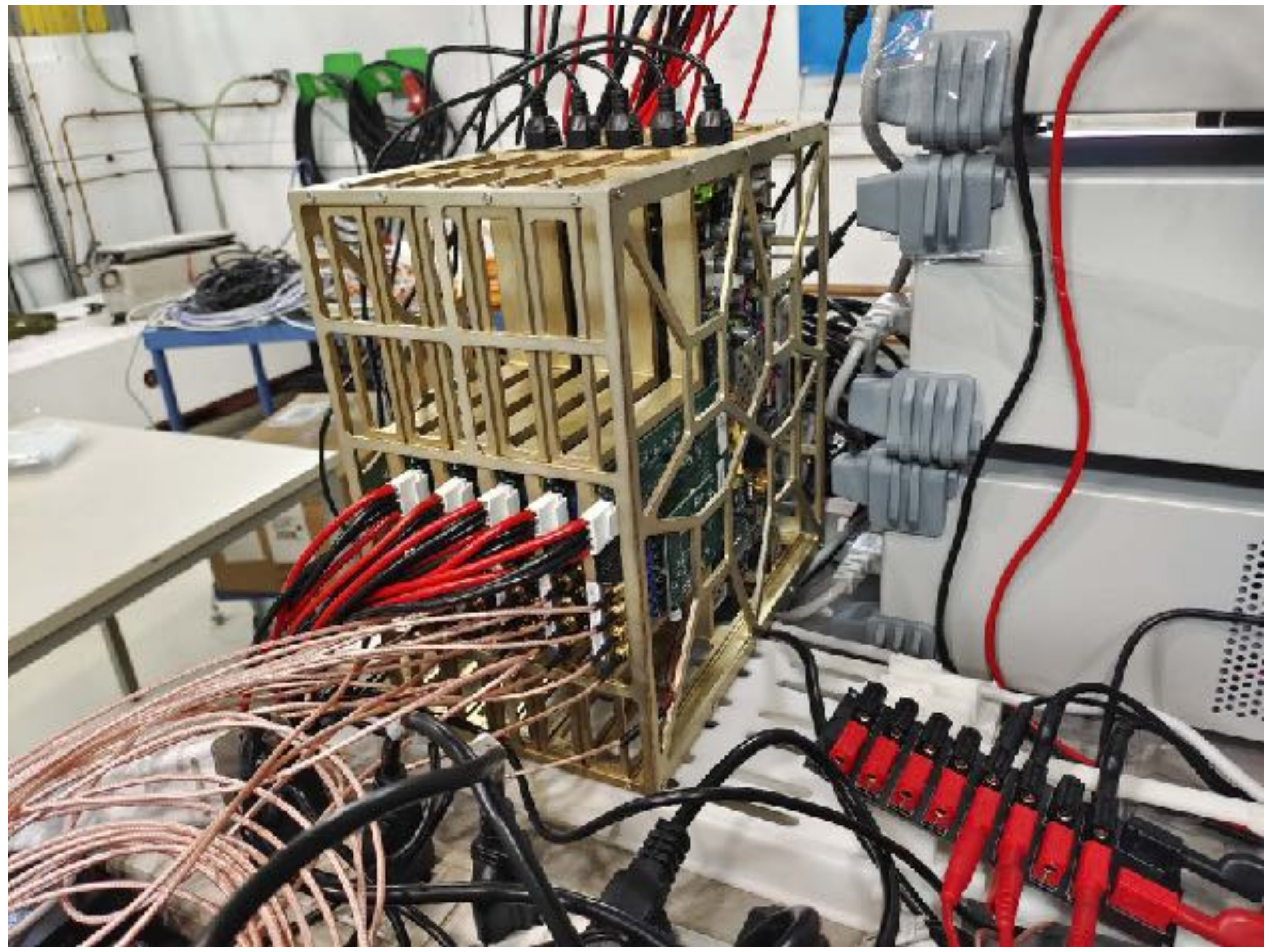
DUT的总效率：97.3%

Test Setup at DESY TB21





Test Setup @ DESY May.2023



- The electron or positron beams are converted bremsstrahlung beams from carbon fibre targets in the electron–positron synchrotron DESY II.
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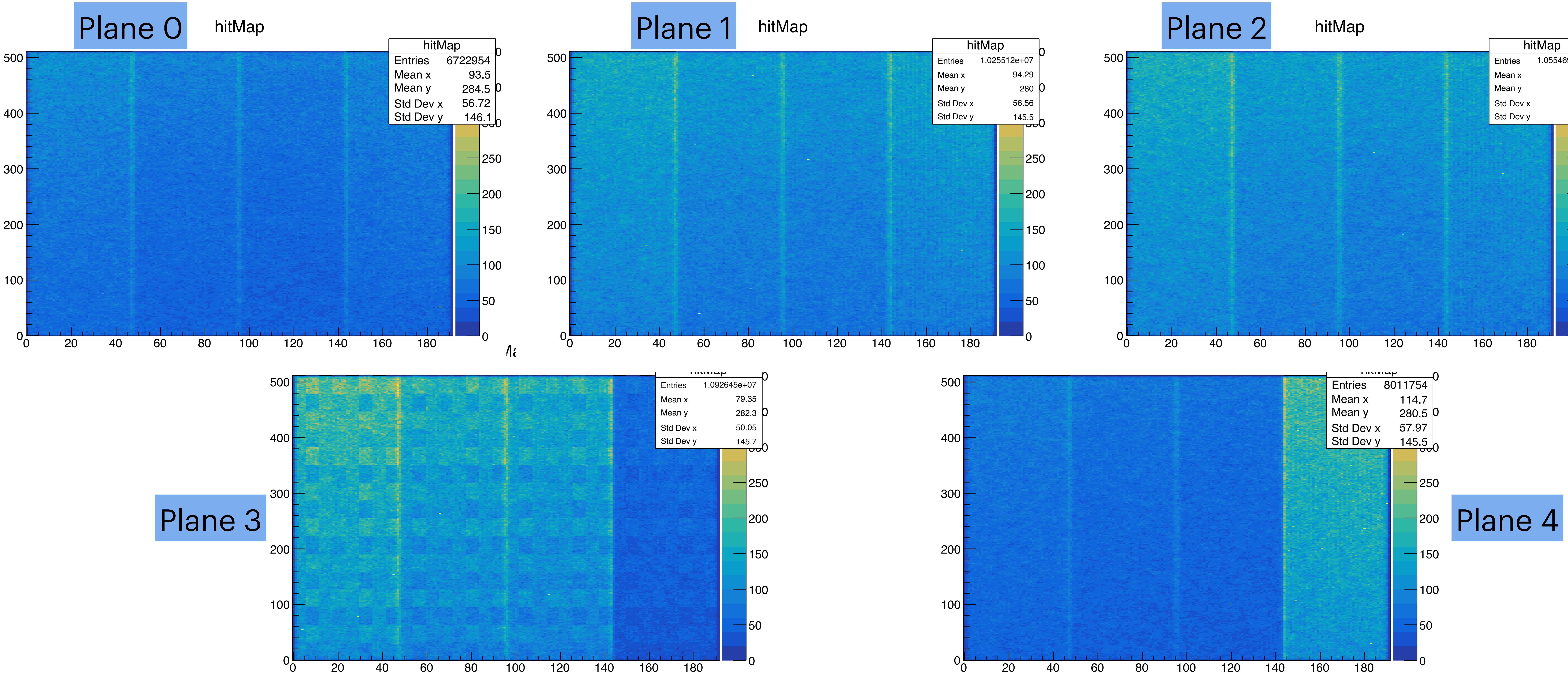
- 5 层MIMOSA26束流望远镜
- TaichuPix–3顶点探测器原型
- 5层JadePix–3束流望远镜
- 大部分实验时间束流能量为5GeV–6GeV

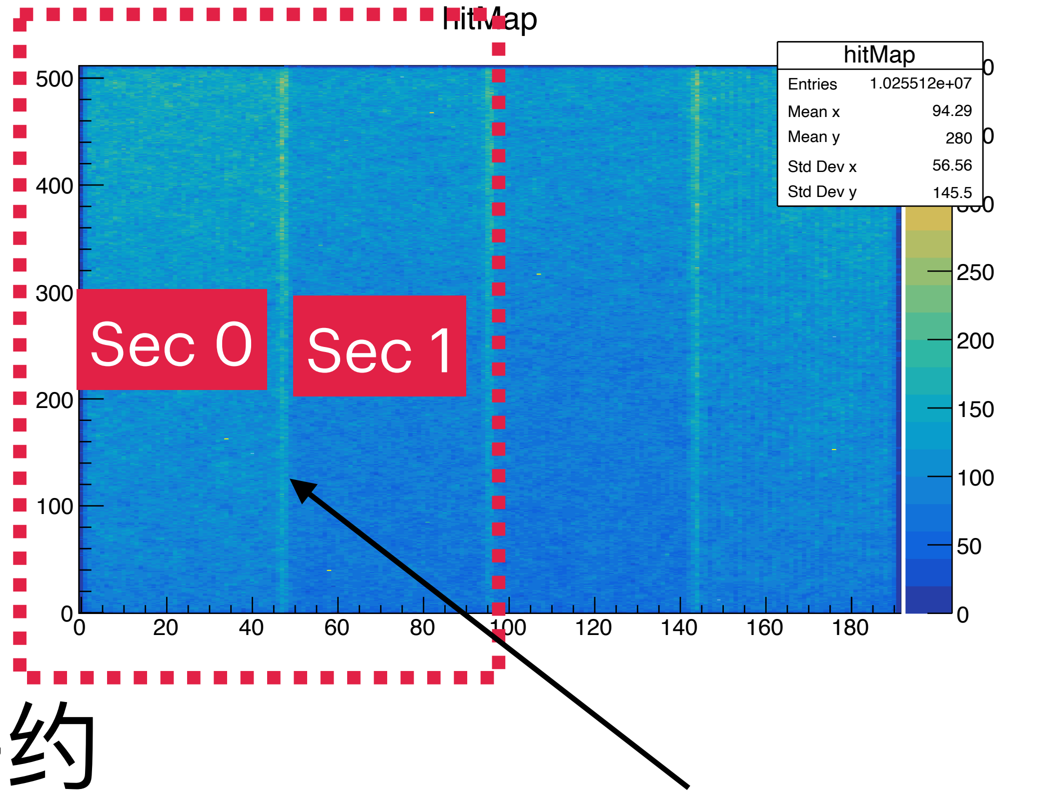
Hitmap

- 每个平面有3/4/1/6/10个像素被屏蔽。
- Plane3的命中率并不像预期的那样好，这个平面产生的数据比其他平面多，可以看到“马赛克”，暂不展示5层重建结果

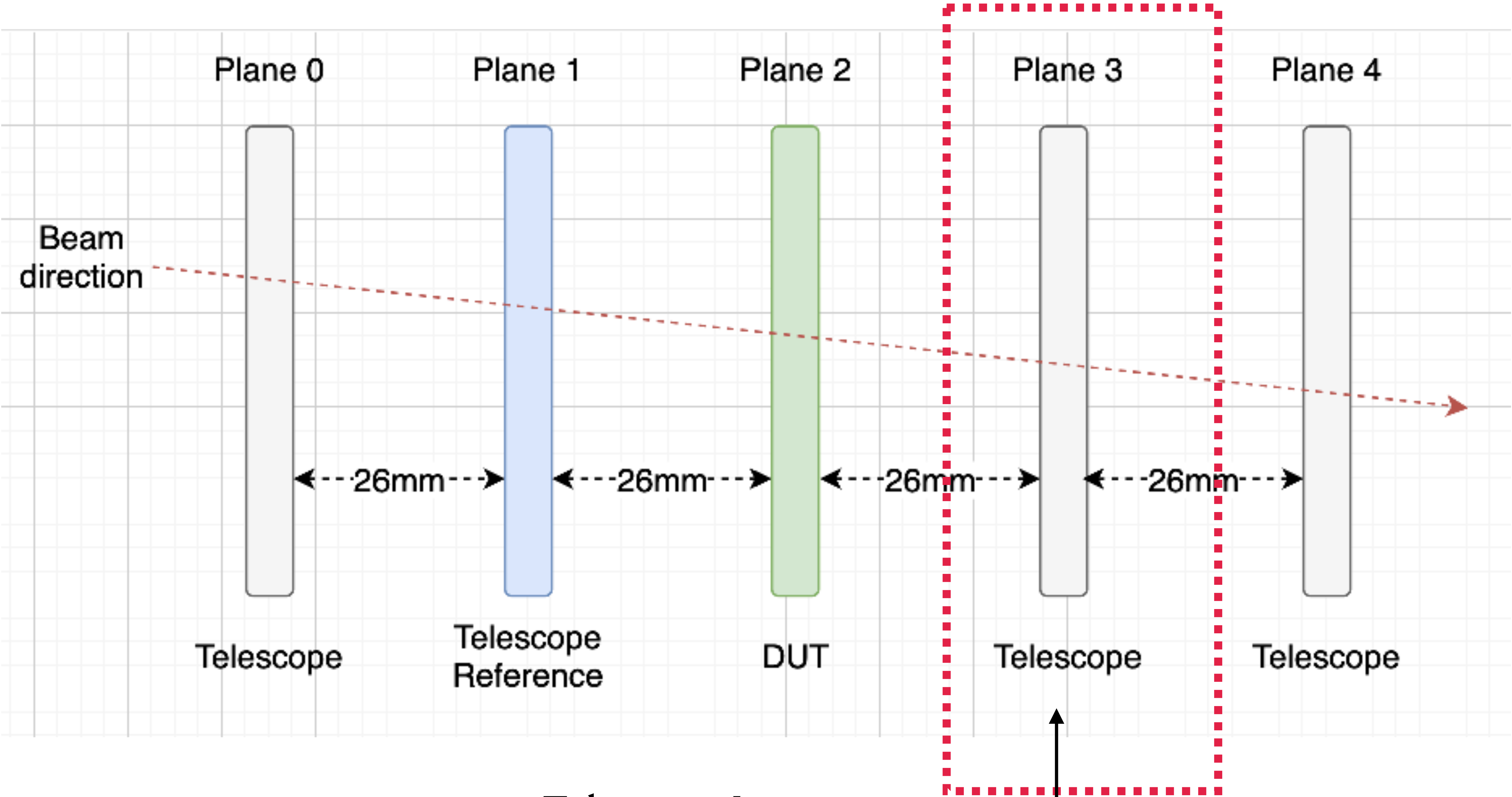


束流望远镜结构和位置偏移

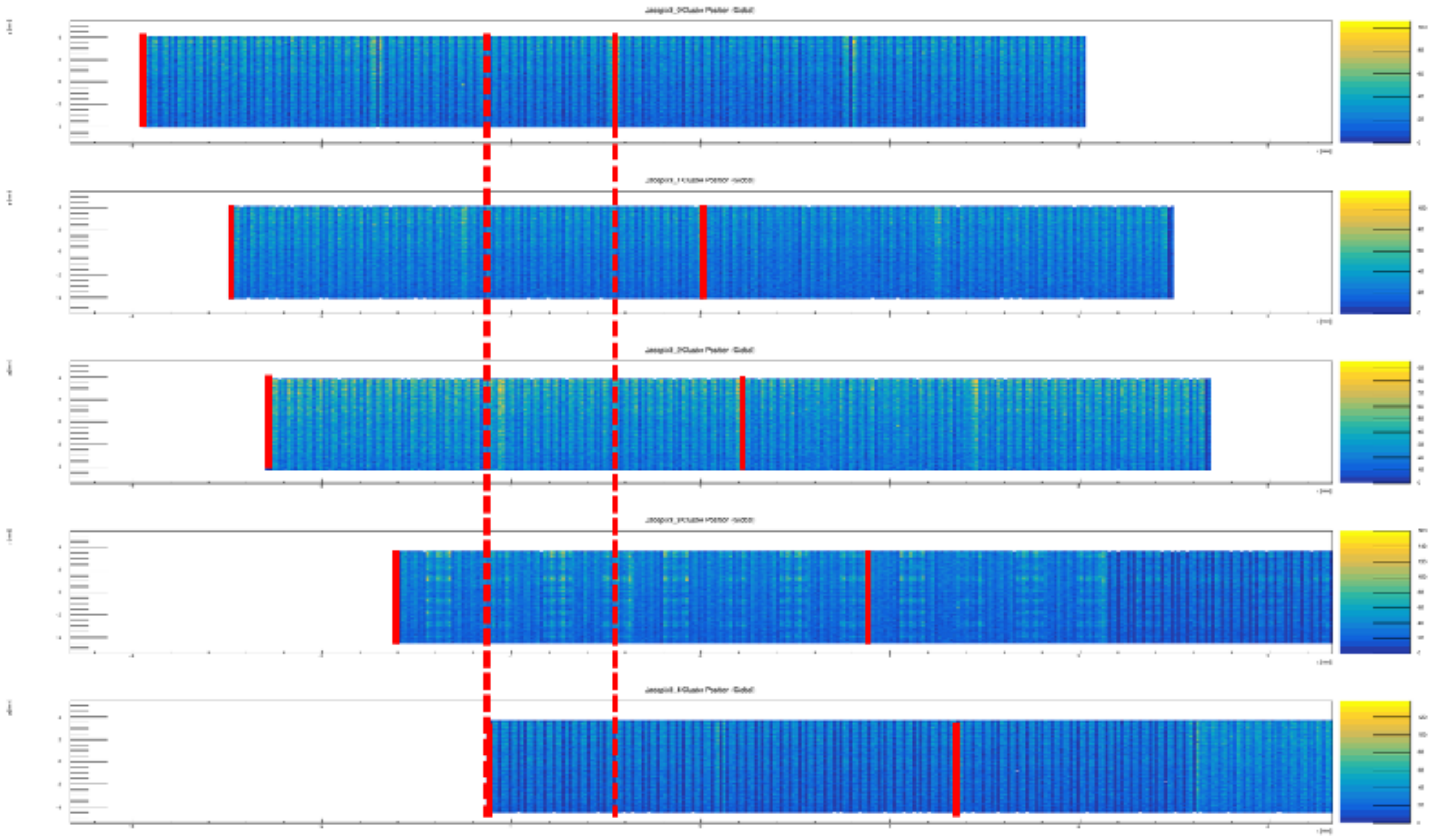
- 通常情况下，Plane 0/1/3/4被设置为望远镜平面，平面2被设置为DUT（被测设备）。
- 由于Plane 3的“马赛克”问题还没有完全清楚，暂时排除Plane3做数据分析
- Alignment发现在束流方向和芯片的X方向之间有一个1度的倾斜角，导致每层x方向偏移约450um，Plane0/4会偏移一个Sector以上宽度



The region of interest (**ROI**)



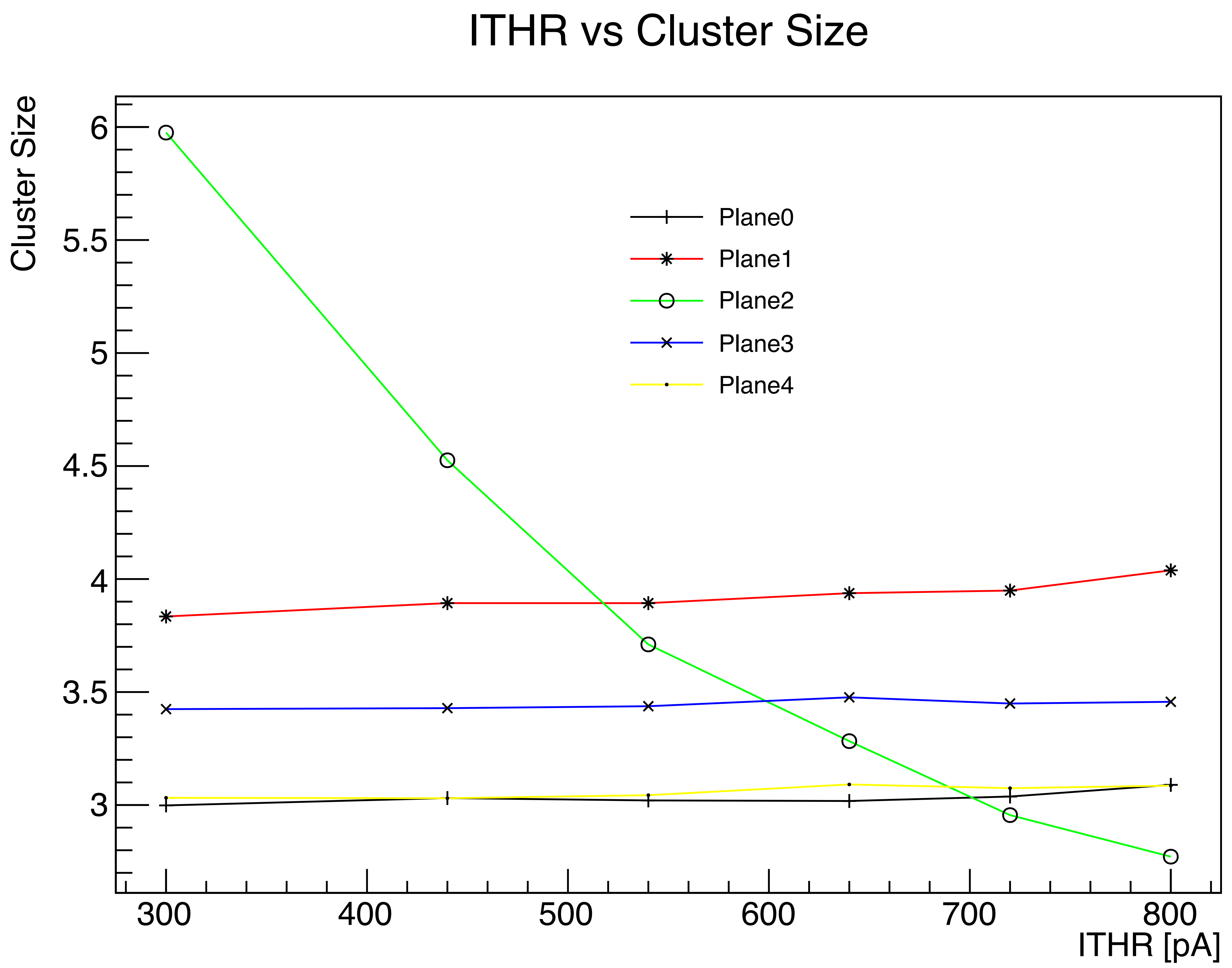
Telescope Layout

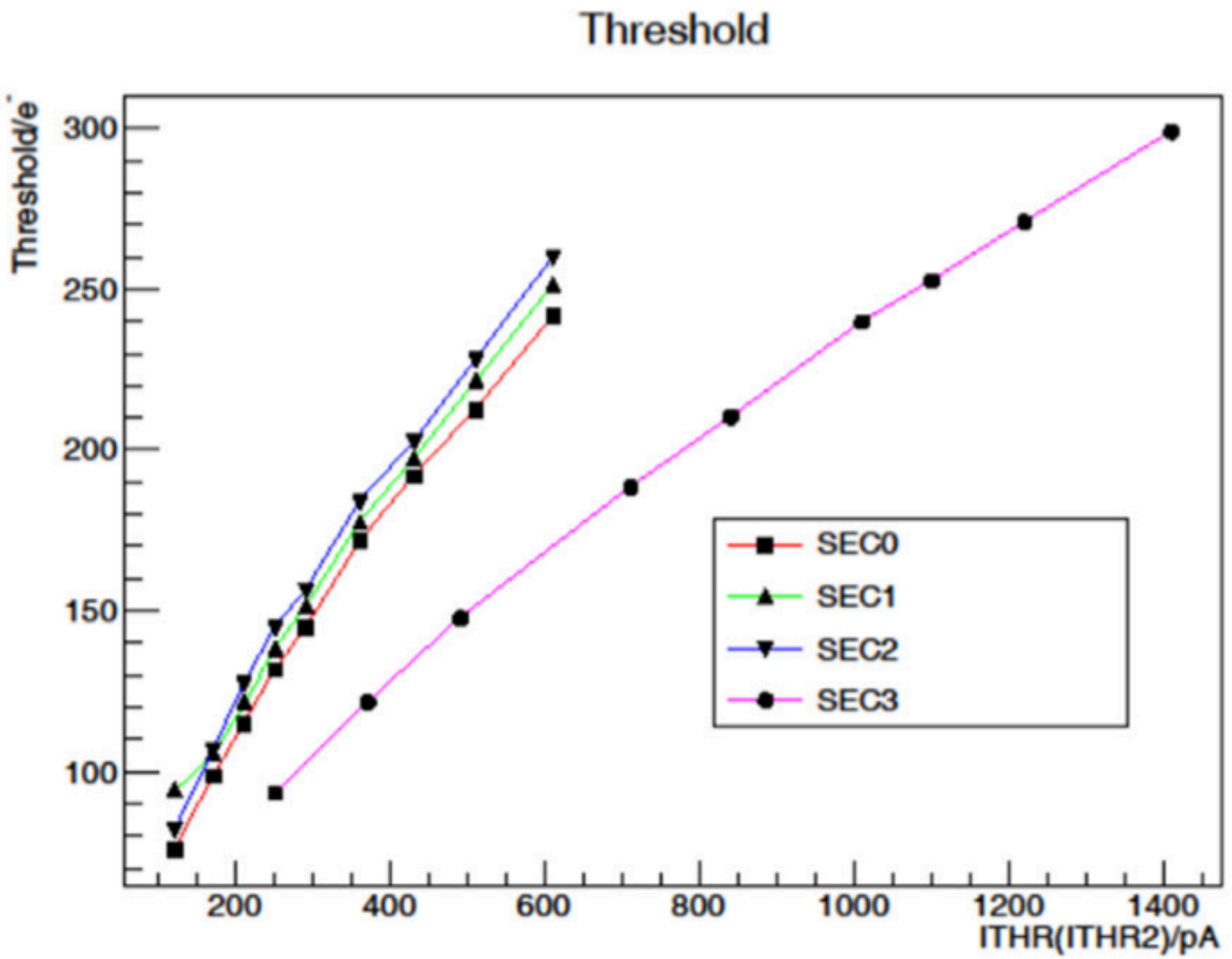


Cluster Distribution

Plane3 is not adopted in resolution and efficiency analysis for now.

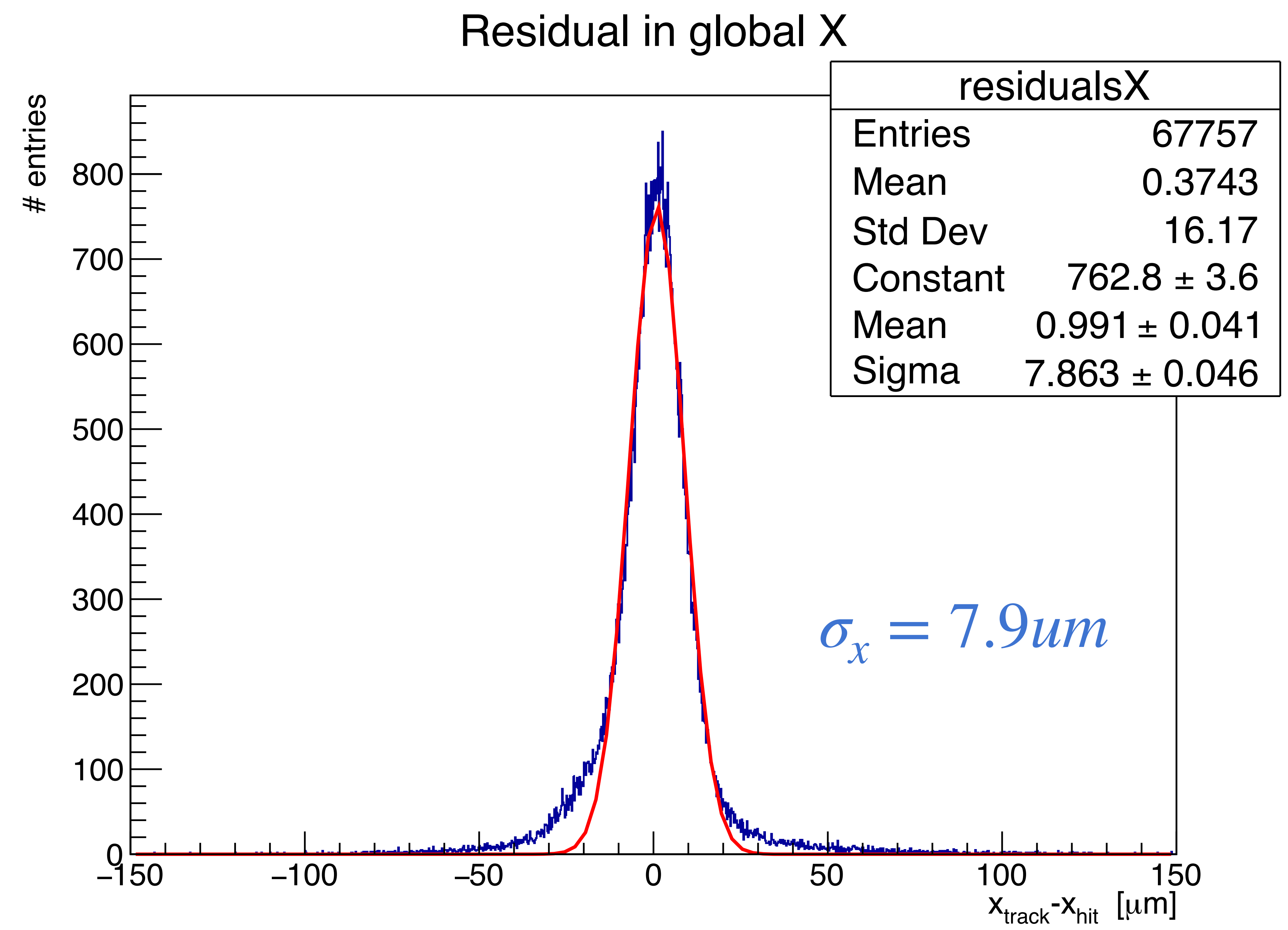
Cluster Size



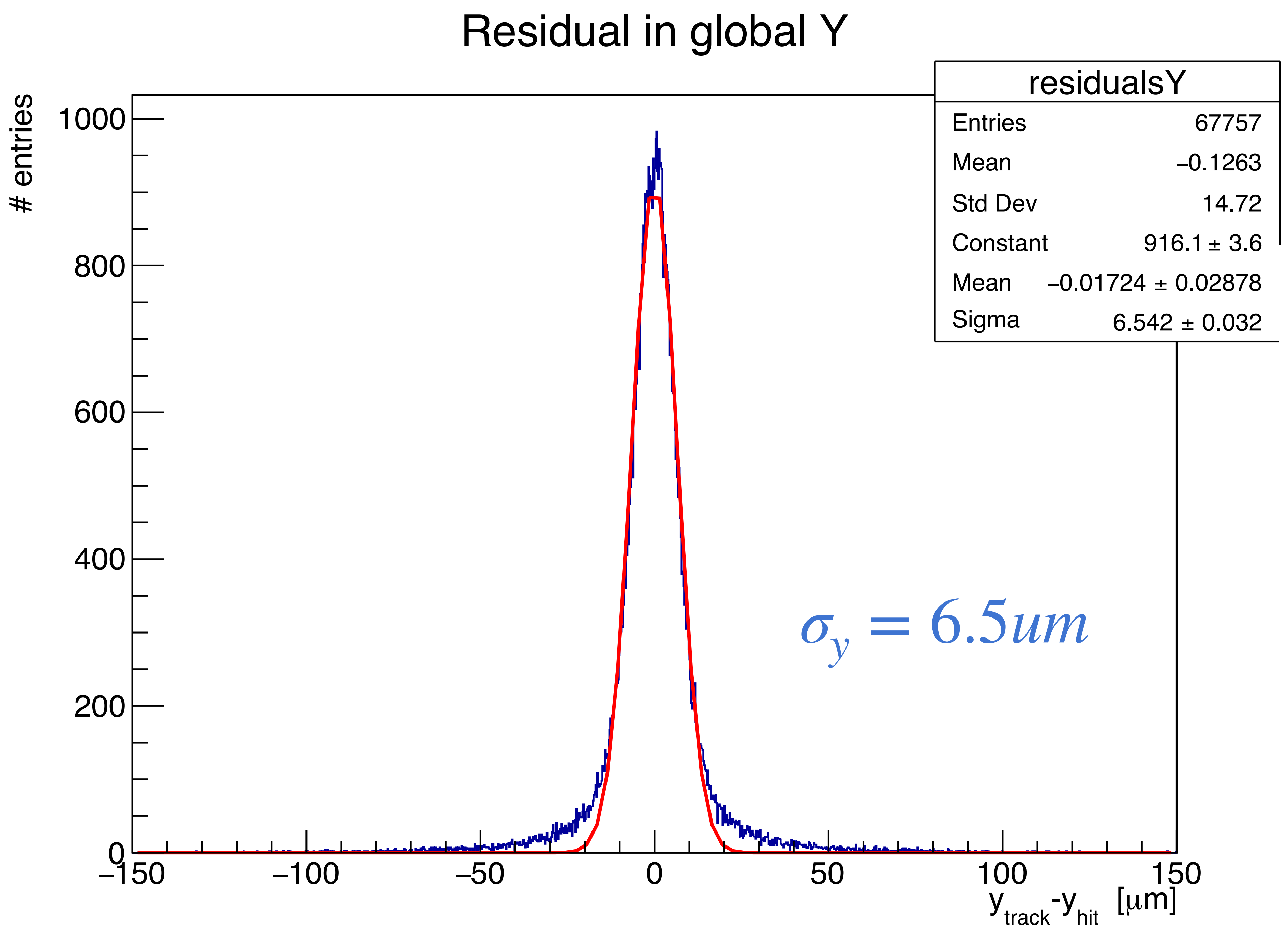


- 阈值扫描只扫描DUT，即Plane2，其它望远镜层阈值为默认阈值500pA($220e^-$)
- 阈值从330pA增加到800pA，Cluster Size大小从6.0减少到2.8

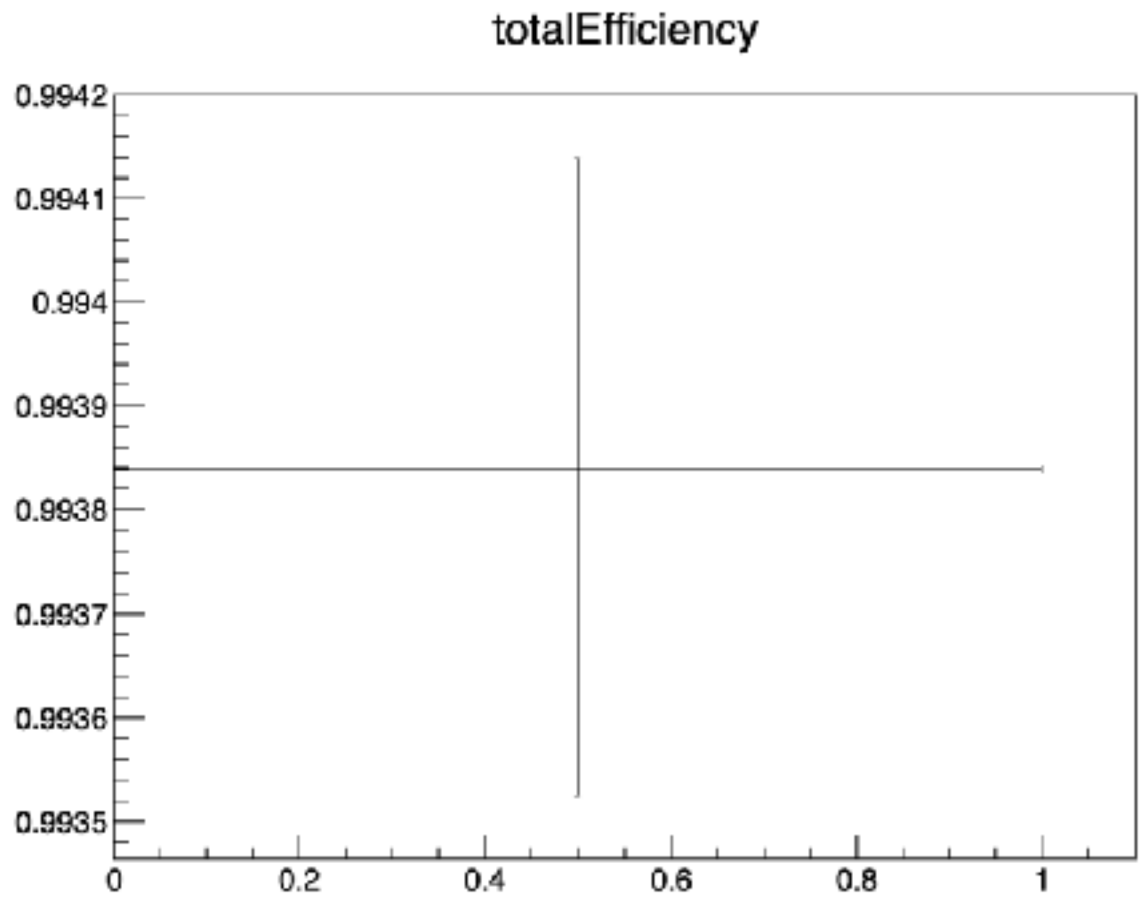
DUT Spatial Resolution



DUT Residual X



DUT Residual Y



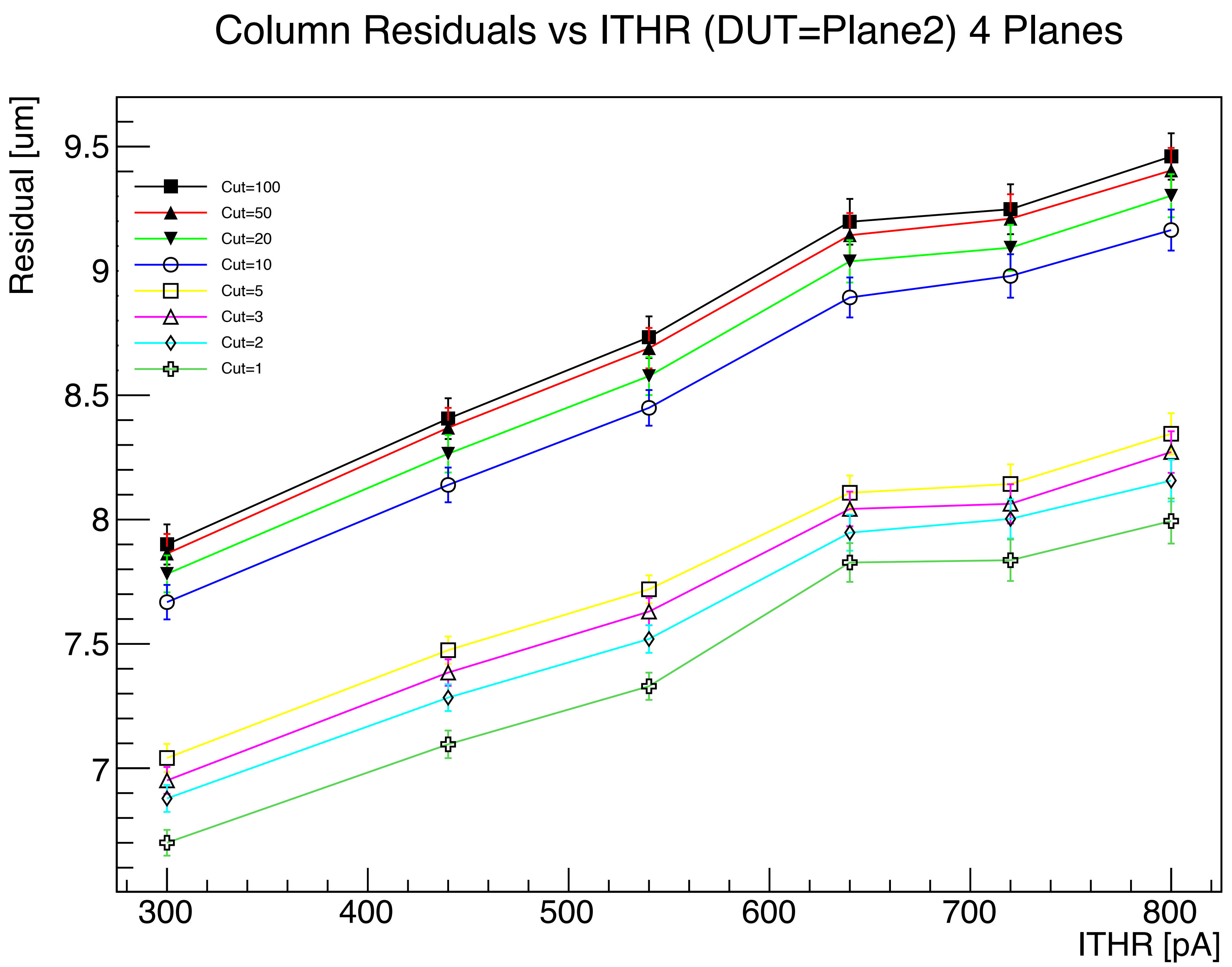
Total Efficiency ~99.38%

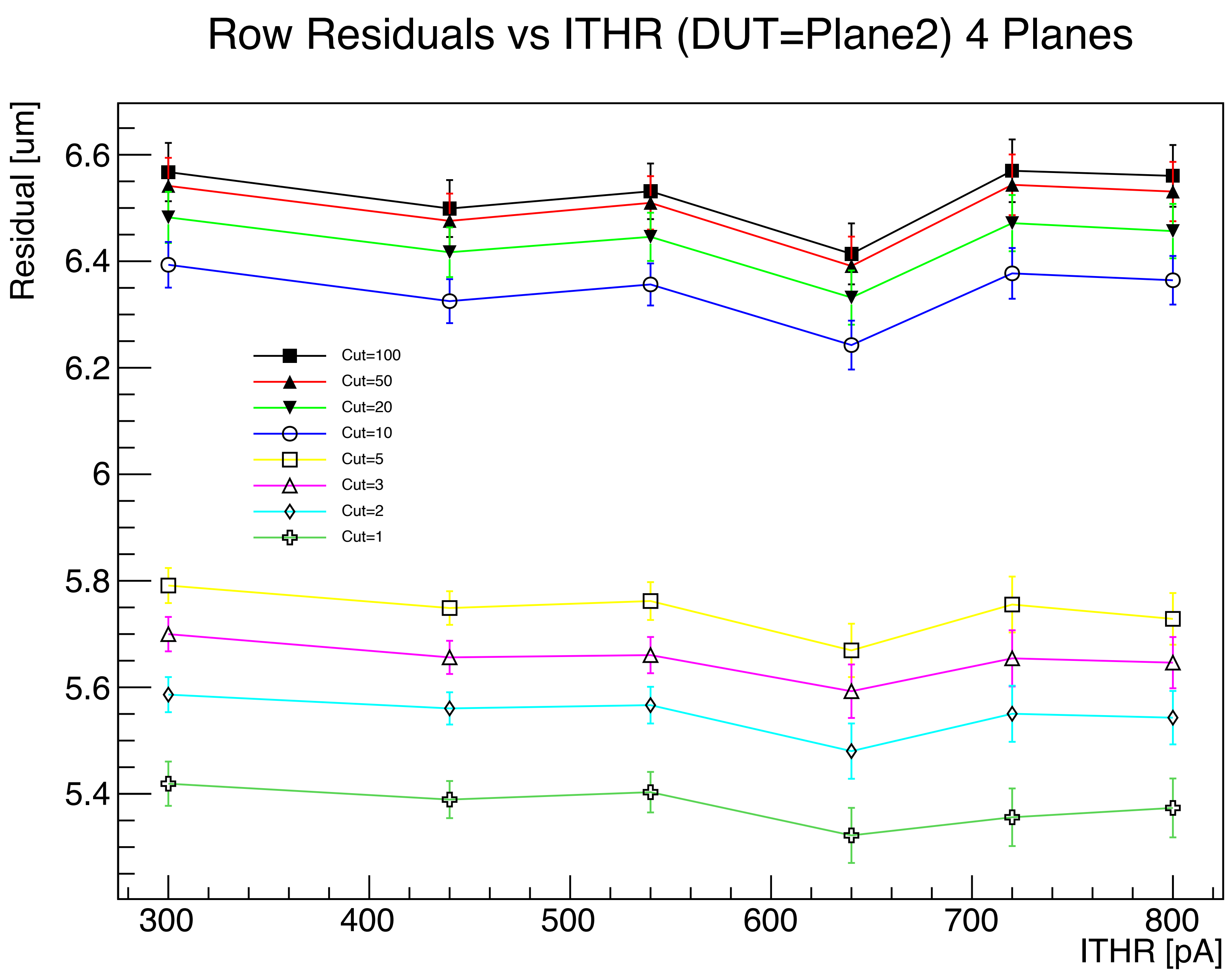
$\sigma_x(tel) = 4.0\ um, \sigma_y(tel) = 3.3\ um$ $\sigma_x(DUT) = 6.8\ um, \sigma_y(DUT) = 5.6\ um$

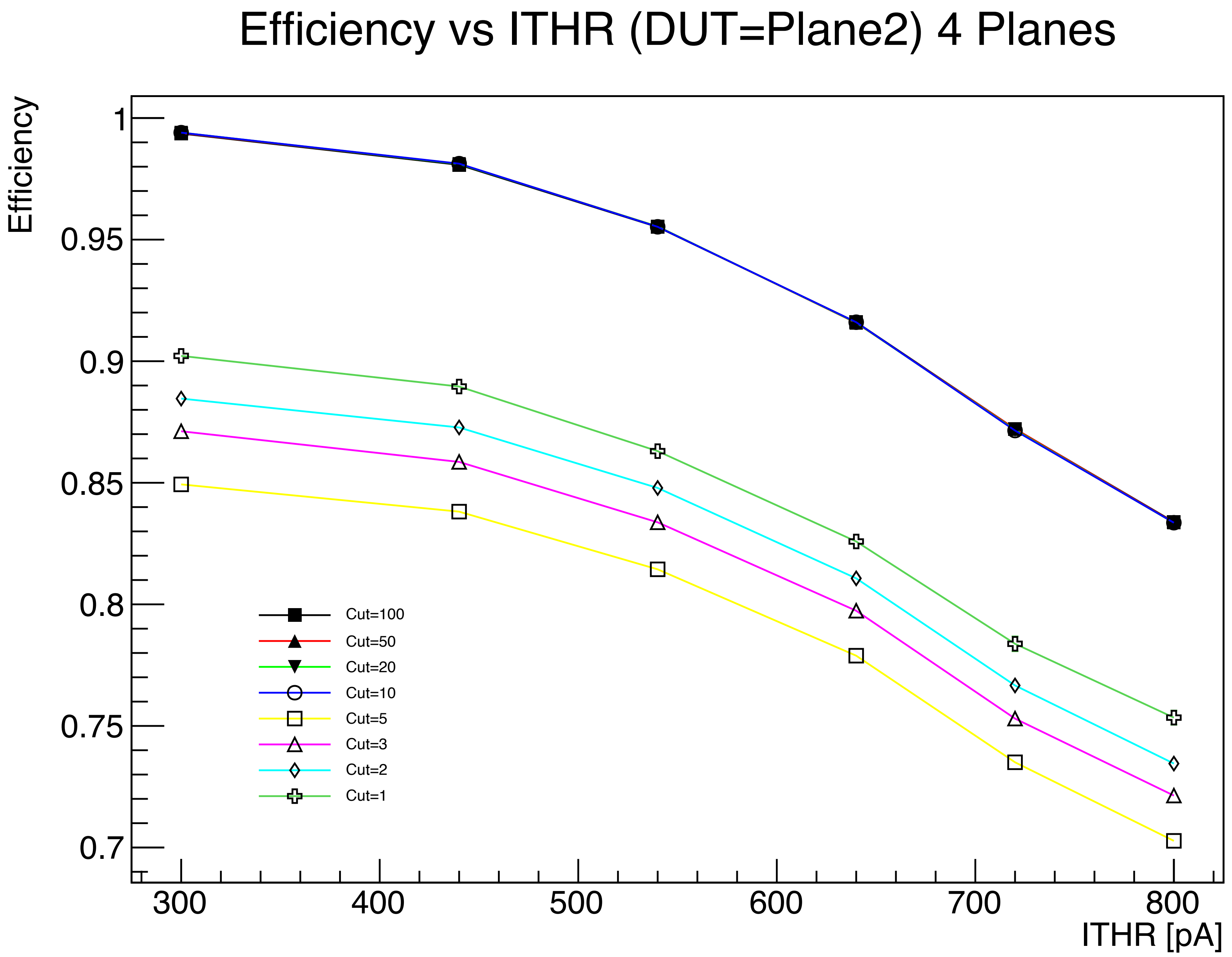
ITHR=300pA(~150e)，DUT在x和y方向的残差分别为6.8um和6.4um，分辨率变差原因：1. 望远镜拓扑结构变差 2. Sector间边界影响

探测效率～99.38%

Residuals and Efficiency







无Cut情况下，随着ITHR的增加（从~150e⁻到~300e⁻）：

- X方向的残差sigma从8.0增加至9.5
- Y方向上没有明显的趋势，原因未知
- 探测效率从99%降低到84%

总结

1. 基本实现JadePix-3束流望远镜研究其中两个初衷：通用多芯片读出系统、离线重建算法
2. 通过束流测试得到JadePix-3空间分辨、探测效率指标：
   - 在列和行方向的空间分辨率达到$5.4um$ 和$4.1um$
   - 探测效率可达~99.3%

展望

1. 5层束流望远镜测试数据完全分析
2. 将JadePix-3束流望远镜应用与JadePix-4/CPV4-3D性能测试中

致谢

- 非常感谢TaichuPix小组提供3次束流测试机会
- 感谢DESY和BSRF对我们实验的支持

谢谢聆听!

Backup

Alignment

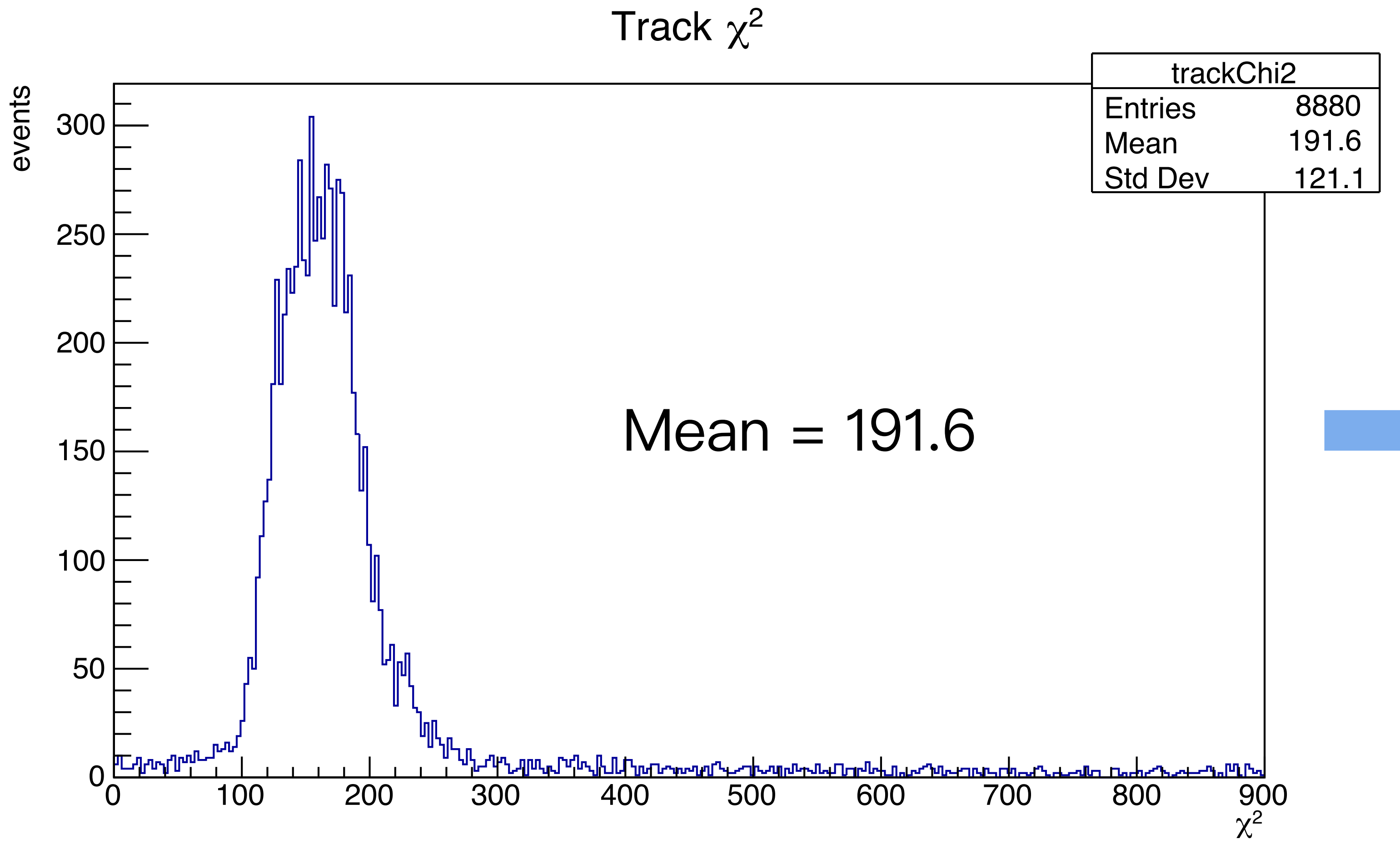
Pre–alignment method:

- Using the mean offset values in X and Y as the required translational shift to update the geometry.

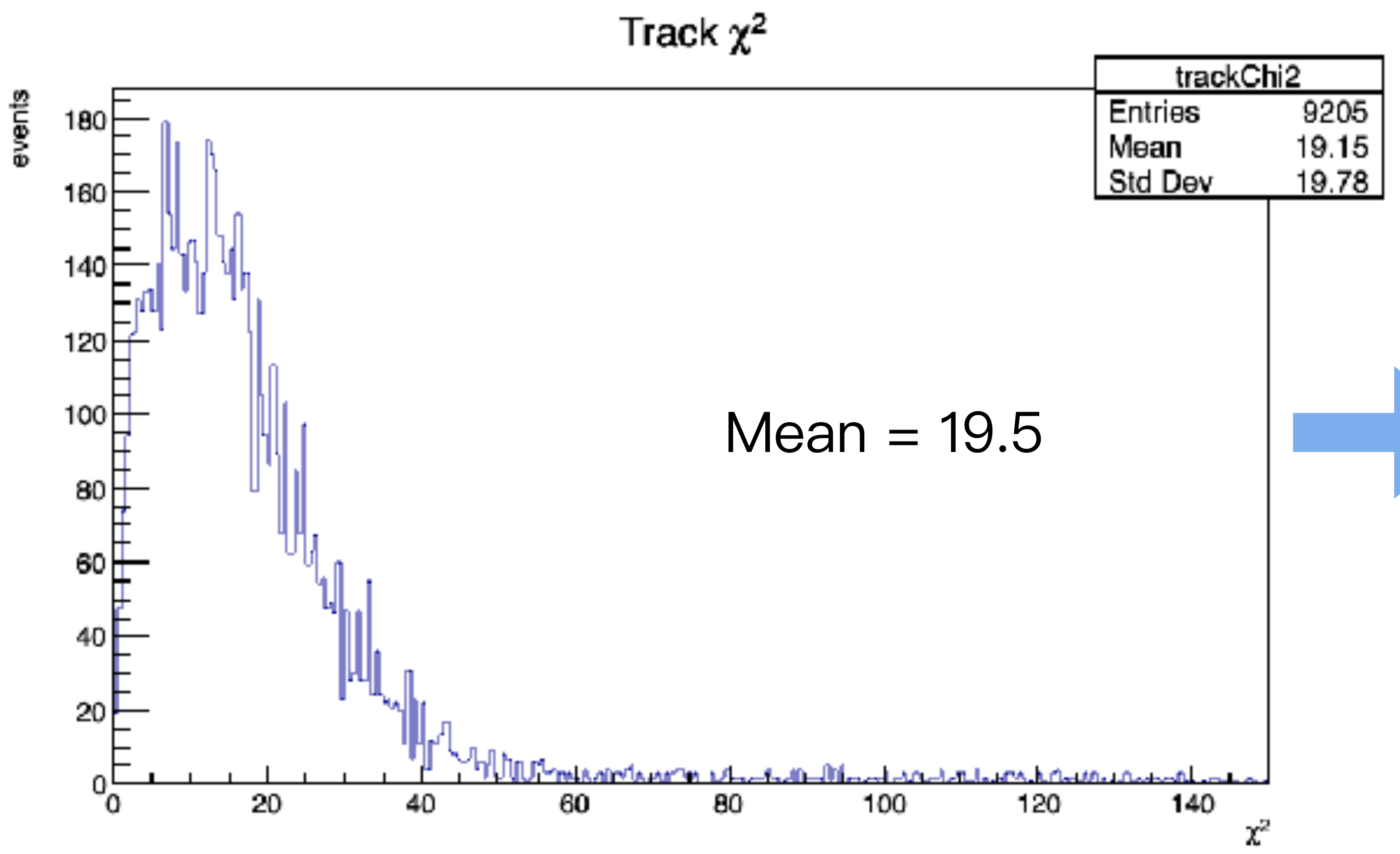
Alignment method:

- Perform translational alignment and rotational alignment using tracks
- Refit all of the tracks and the minimize the χ^2 of tracks

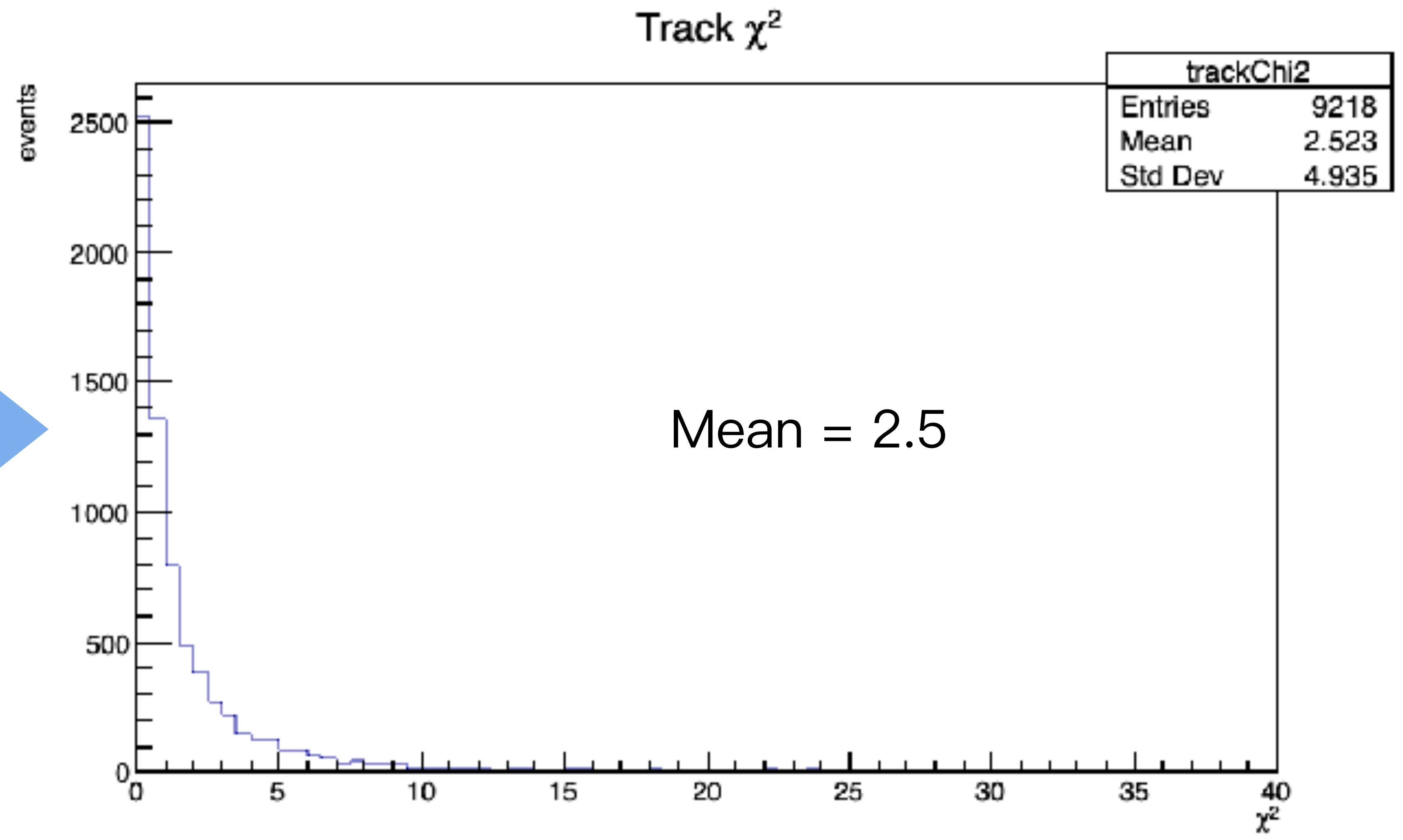
The mean value of χ^2 distribution will drop very significantly after alignment. (191.5 –> 19.5 –> 2.5)



χ^2 distribution before pre–alignment



χ^2 distribution after pre–alignment



χ^2 distribution after fine–alignment

Alignment

The alignment procedure includes 2 steps:

1. Align the telescope plane, and ignore the DUT

- Pre–alignment (x, y geometry)
- Fine alignment (x, y geometry and x, y, z orientation)

2. Align the DUT, and freeze telescope geometry

- Pre–alignment (x, y geometry)
- Fine alignment (x, y geometry and x, y, z orientation)

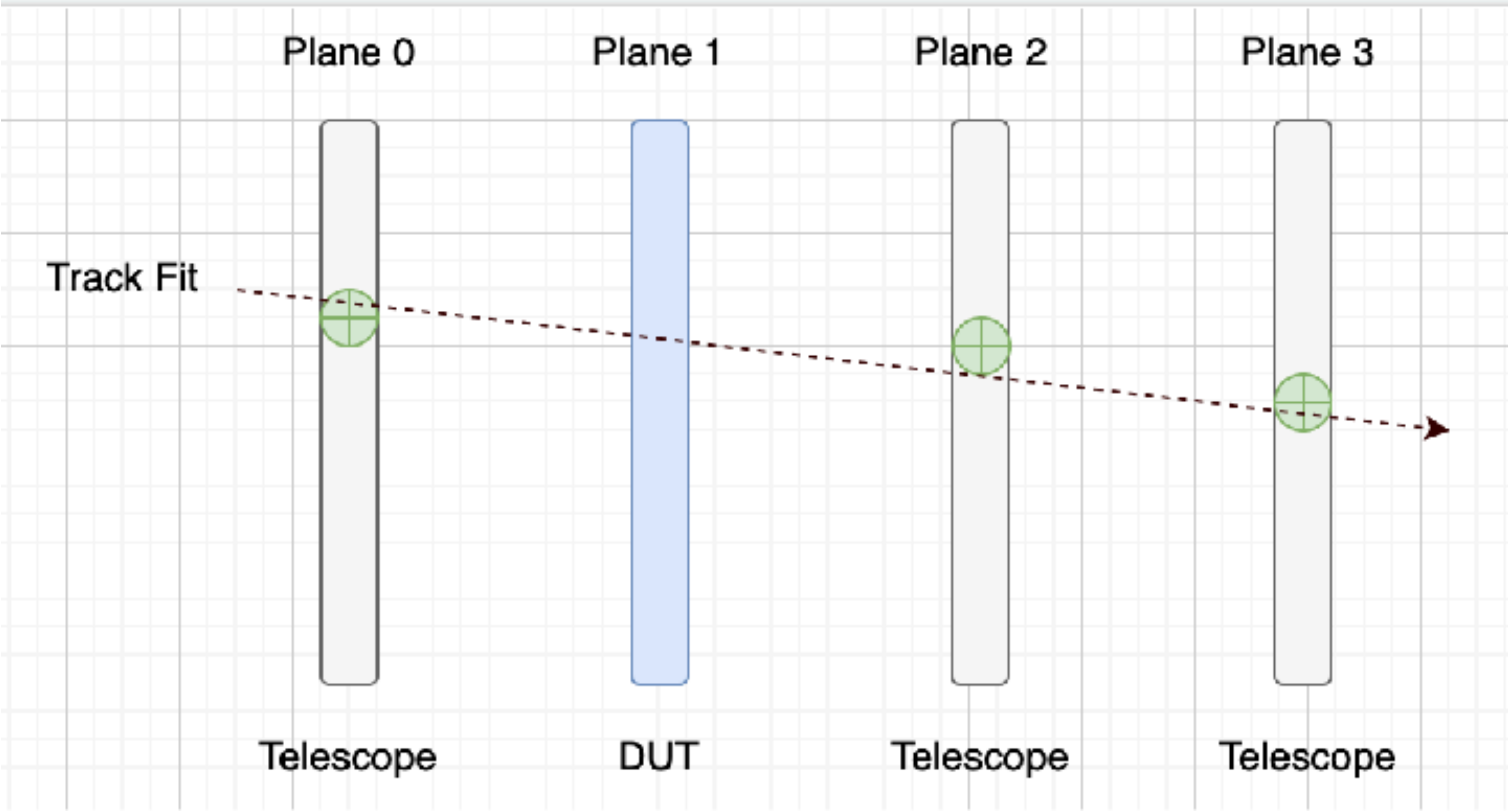


Fig.1 Tracking Fitting

- While tracking, the path of the particle is described as a straight line, **ignoring the effect of multiple scattering**.
- Hit uncertainties are taken into account.
- The χ^2 is defined by the resolution weighted sum of residuals r_p in global coordinates:

$$\chi^2 = \sum_{p=0}^{N} \frac{{r_{p_x}}^2}{\sigma_{p_x}} + \frac{{r_{p_y}}^2}{\sigma_{p_y}}$$

Spatial Resolution

Results from the EUDET telescope with high resolution planes, https://doi.org/10.1016/j.nima.2010.03.015

- The single plane resolution (σ_{DUT}) can be obtained from the measured residual width (σ_{meas}) and the telescope resolution width (σ_{tel}) using equation (1):

$$\sigma_{meas}^2 = \sigma_{DUT}^2 + \sigma_{tel}^2 \quad (1)$$

- The telescope resolution can be determined **assuming that the reference planes all have the same intrinsic resolution, using equations** (2) (3):

$$\sigma_{meas}^2 = k\sigma_{plane}^2 \quad (2), \quad k = \frac{\sum_i^N z_i^2}{N\sum_i^N z_i^2 - (\sum_i^N z_i)^2} \quad (3)$$

- **If the device under test is of the same type of the reference planes**, the intrinsic resolution of the single telescope plane and of the overall telescope can be derived directly from measured residual width:

$$\sigma_{plane}^2 = \frac{\sigma_{meas}^2}{1+k} \quad (4) \quad \text{and} \quad \sigma_{tel}^2 = \frac{k}{1+k}\sigma_{meas}^2 \quad (5)$$