

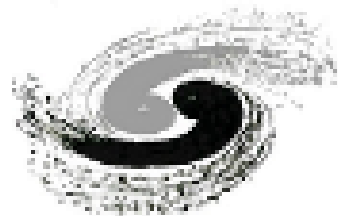
# 下一代高时间与高位置分辨 AC-LGAD传感器及 专用读出芯片LATRIC 研发与测试

第十二届高能物理全国会议

2026年7月13-19日

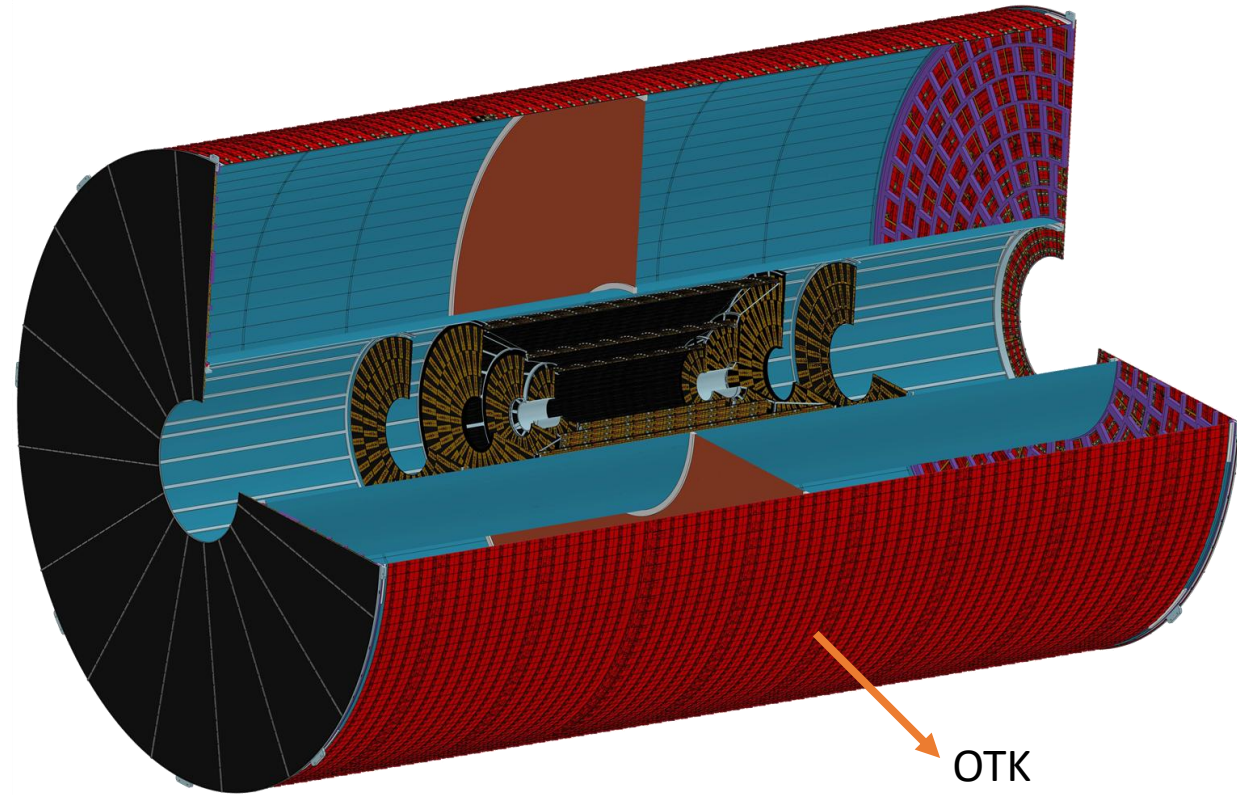
张嘉健 代表 CEPC OTK 组.

高能物理研究所



# CEPC Outer Tracker (OTK) 探测器

- OTK 是环形正负电子对撞机 (CEPC) 探测器径迹系统的最外层子探测器
- 必须提供：
  - 高精度的空间测量 ( $10\ \mu\text{m}$ ) 以提升动量分辨率;
  - 精确的时间测量 ( $50\ \text{ps}$ ) 以用于基于飞行时间 (TOF) 的粒子鉴别。
- 为此OTK采用AC-coupled Low-Gain Avalanche Detector (AC-LGAD)
  - 配备专用读出芯片LATRIC

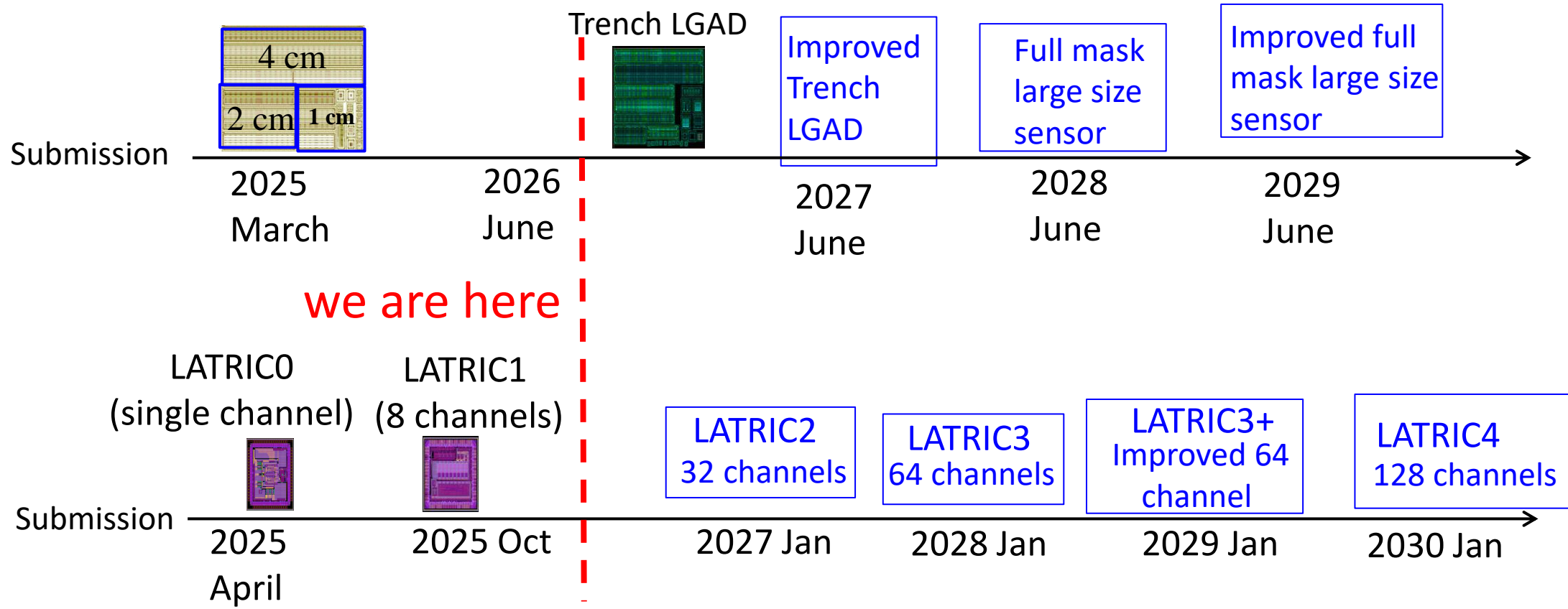


[1] **CEPC Technical Design Report -- Reference Detector**

<https://doi.org/10.48550/arXiv.2510.05260>

# 高能所AC-LGAD与LATRIC的研发计划

- LGAD传感器正朝着更优工艺、更大尺寸、更高性能的方向发展。



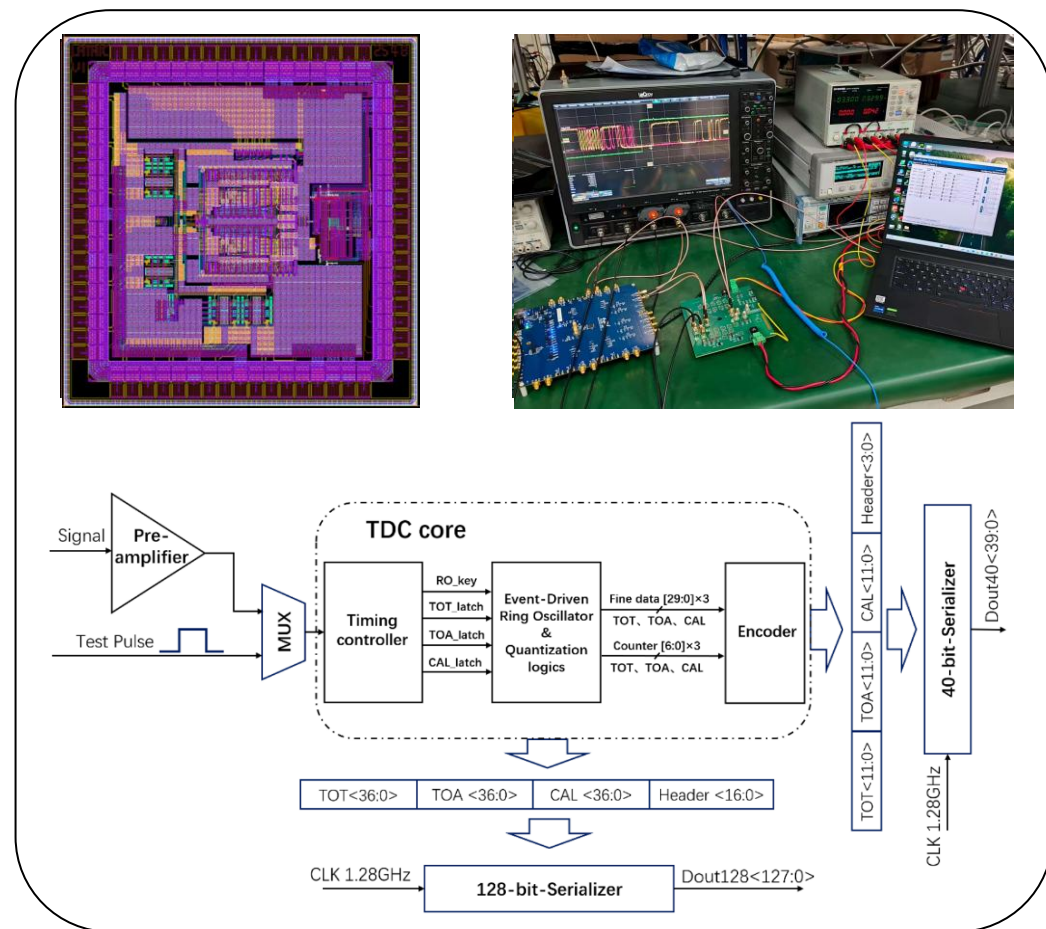
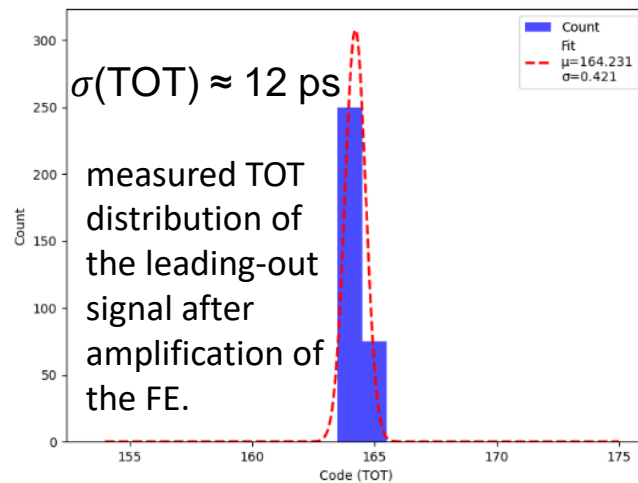
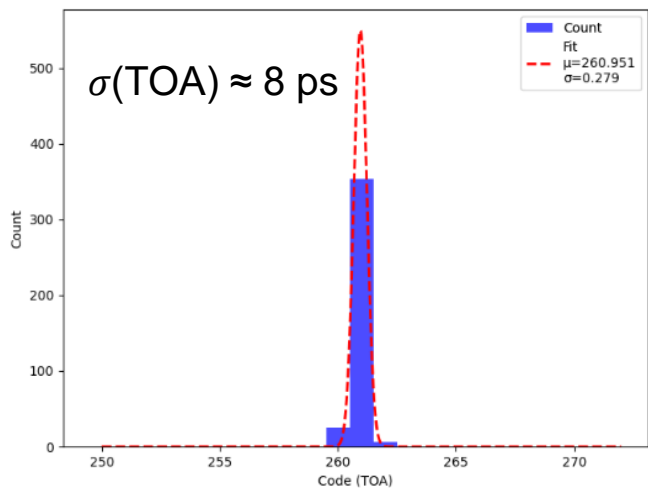
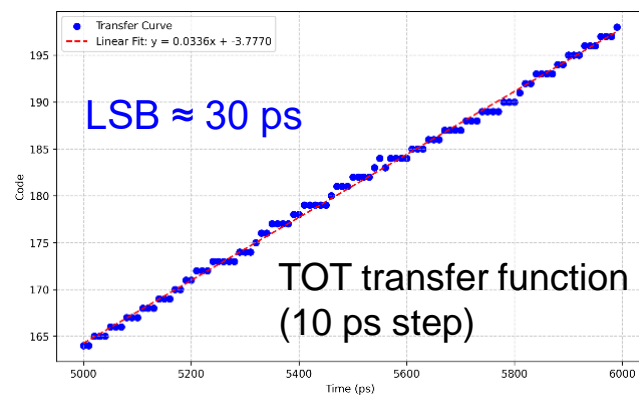
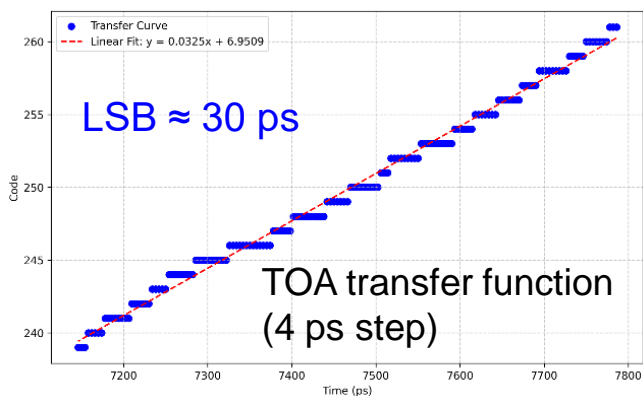
- LGAD读出ASIC LATRIC的研发正朝着多通道与更低功耗方向推进。

# LGAD 读出 ASIC, LATRIC

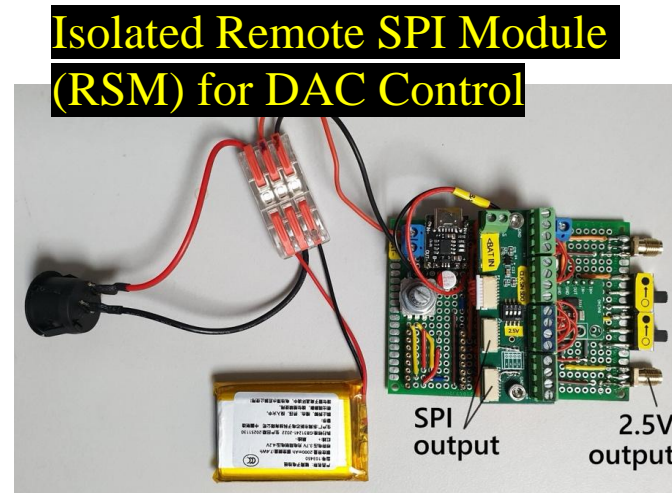
## 首款LATRIC原型芯片LATRIC-V0:

- 采用55nm CMOS工艺制造
- 内部集成前置放大器、甄别器、时间数字转换器 (TDC) 以及用于数据输出的串行器。
- 测试表明其LSB为29.8 ps, 达到了30 ps的设计目标

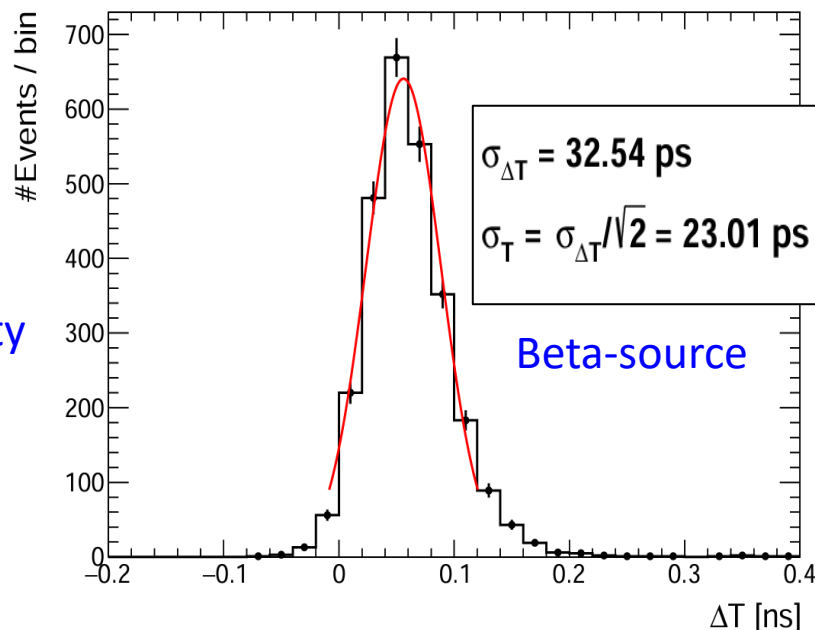
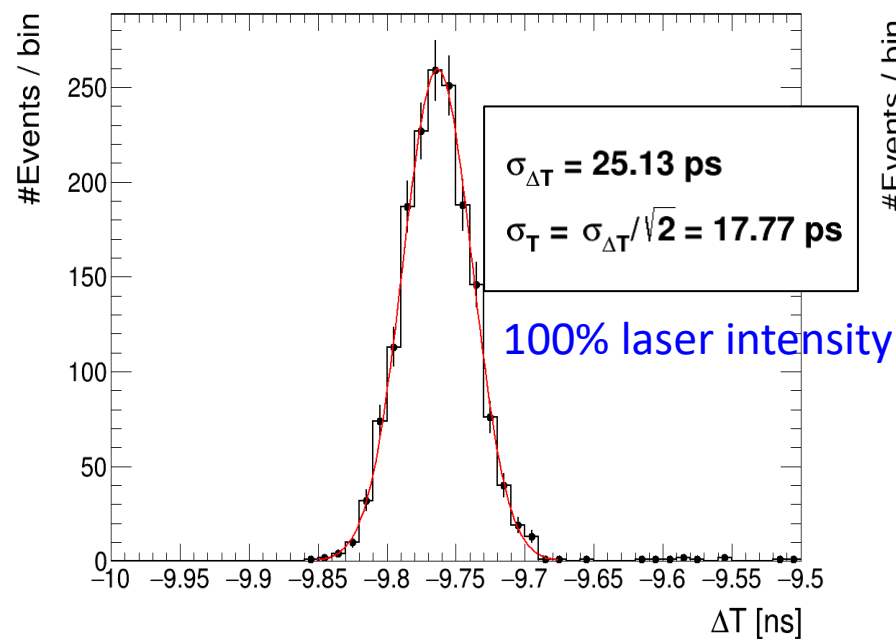
- 实测TDC功耗与设计预期相符
  - 在0.5 MTPS (每秒百万次触发) 下为0.1 mA (1.2 V),
  - 1 MTPS下为0.3 mA,
  - 2 MTPS下为0.5 mA



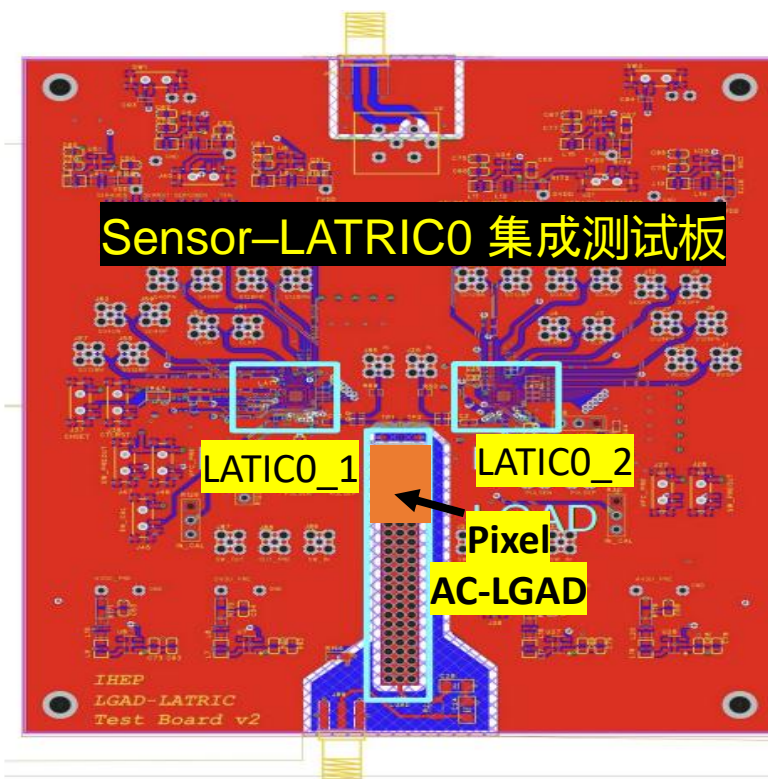
# LATRICO (单通道) 与AC-LGAD 的联合测试



两片LATRICO芯片之间的时间差,  $\Delta T$ 分布



正在开展等效于β粒子的激光强度研究



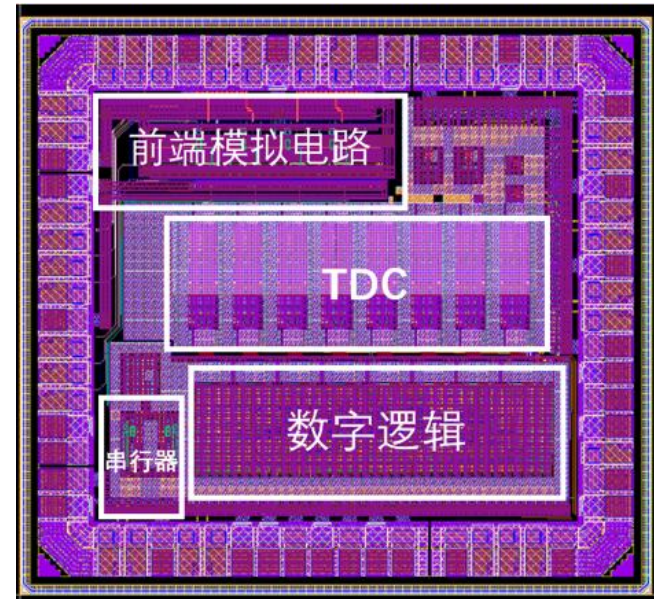
# LATRIC1 (8通道) 读出ASIC的最新进展

## ■ 第二版读出ASIC, LATRIC1

- 通道间距为100  $\mu\text{m}$
- 包含8个通道: 其中4个通道集成模拟前端与TDC, 另外4个通道由连接至差分脉冲接收器的TDC组成

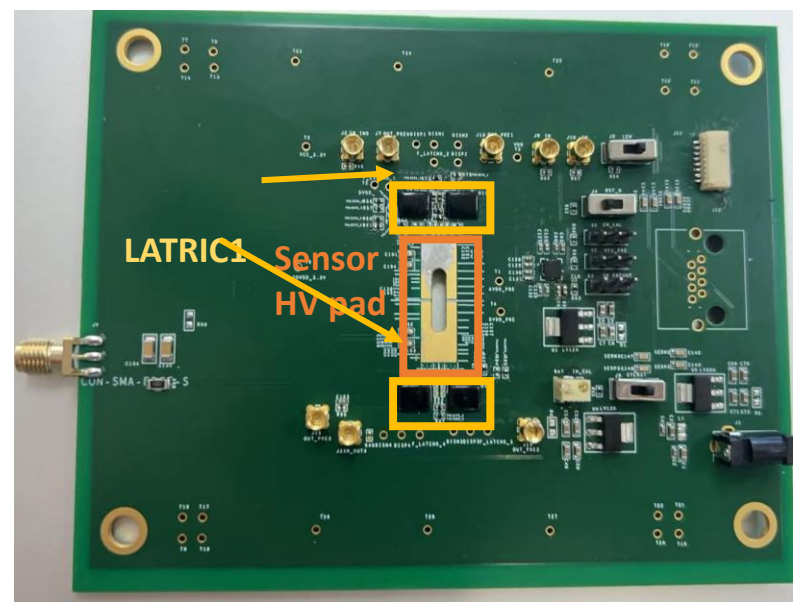
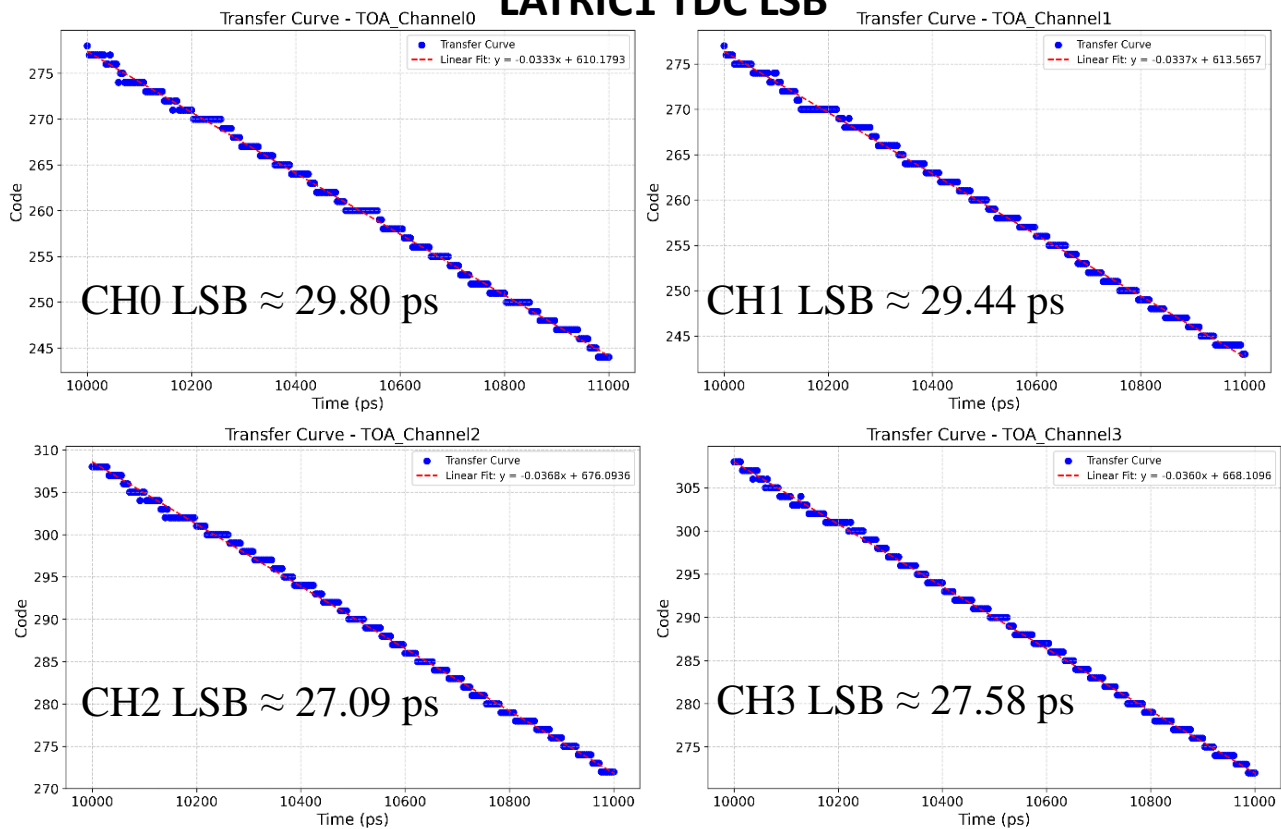
## ■ 性能优化包括:

- 改进前端模拟电路, 提高前置放大器增益以改善信噪比。
- 优化编码器逻辑, 并新增event builder与时间戳功能等。



LATRIC1 layout

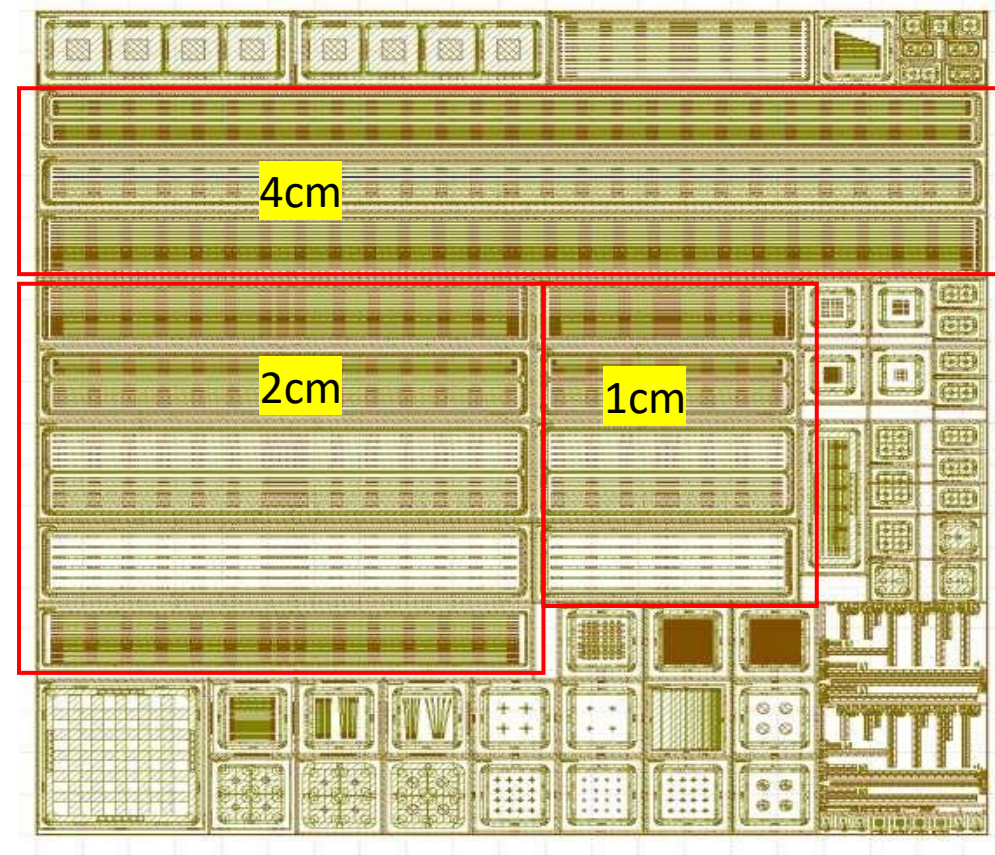
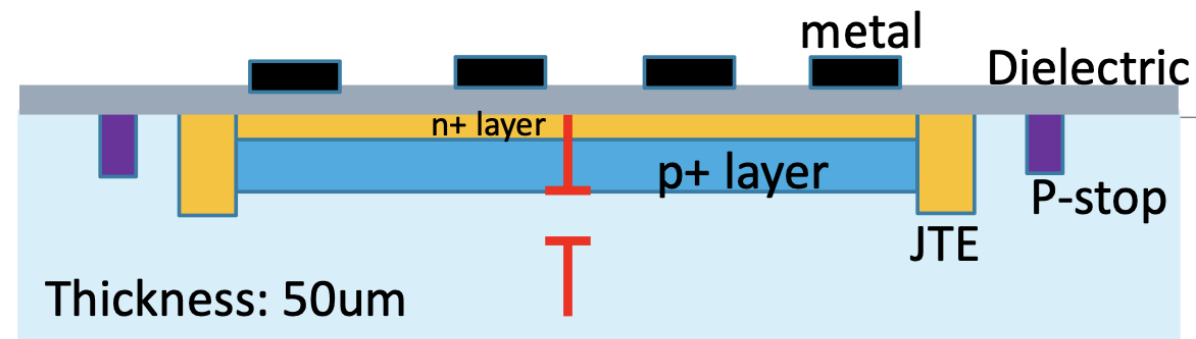
### LATRIC1 TDC LSB



最新版LATRIC1-Sensor 集成测试板

# 长条型AC-LGAD

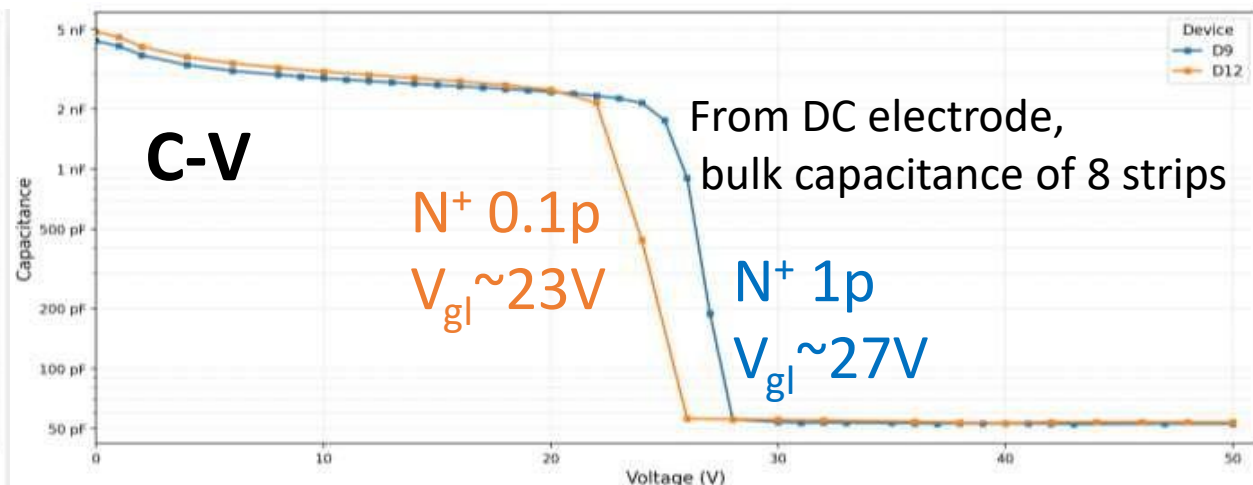
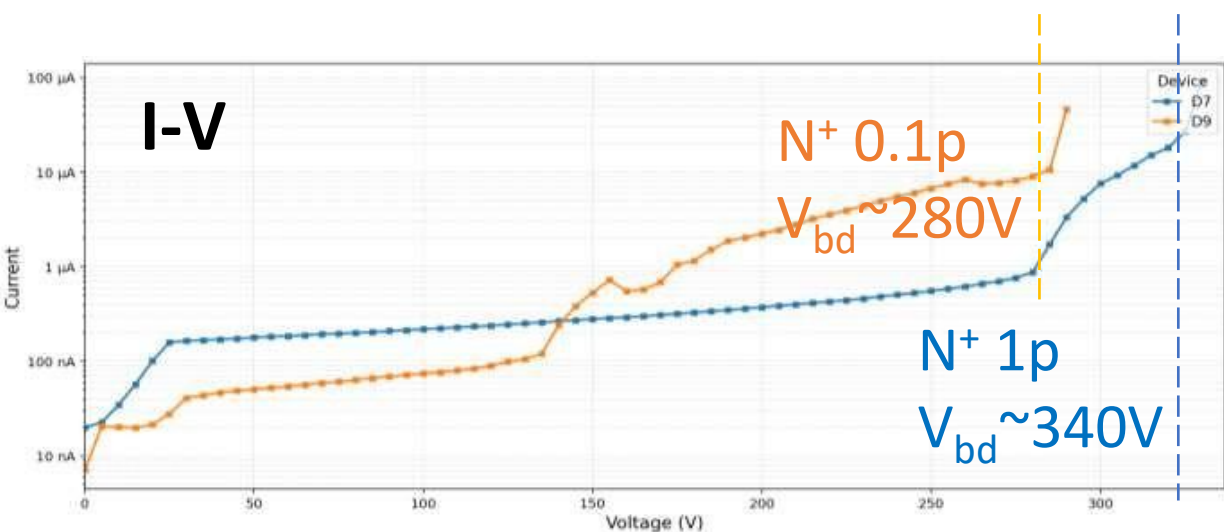
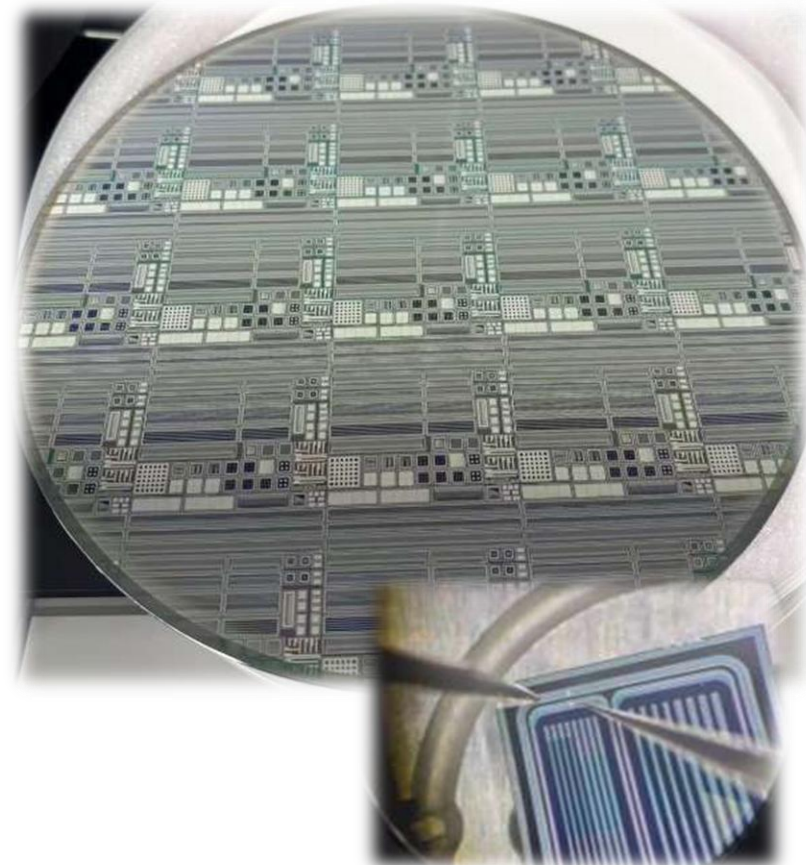
- 2025年4月提交流片
  - 条长：1 cm、2 cm 和 4 cm
  - 条间距：100  $\mu\text{m}$ 、200  $\mu\text{m}$  和 500  $\mu\text{m}$
  - 电极宽度：25  $\mu\text{m}$ 、50  $\mu\text{m}$  和 100  $\mu\text{m}$
  - 隔离结构设计
  - 优化外延层（EPI）厚度（50  $\mu\text{m}$ 、80  $\mu\text{m}$ ）以降低电容，从而降低读出功耗
  - 调节N+掺杂浓度以优化位置分辨性能
- 首批5片晶圆于2025年12月交付。
- 2026年5月交付了2片采用较低N+注入剂量的晶圆



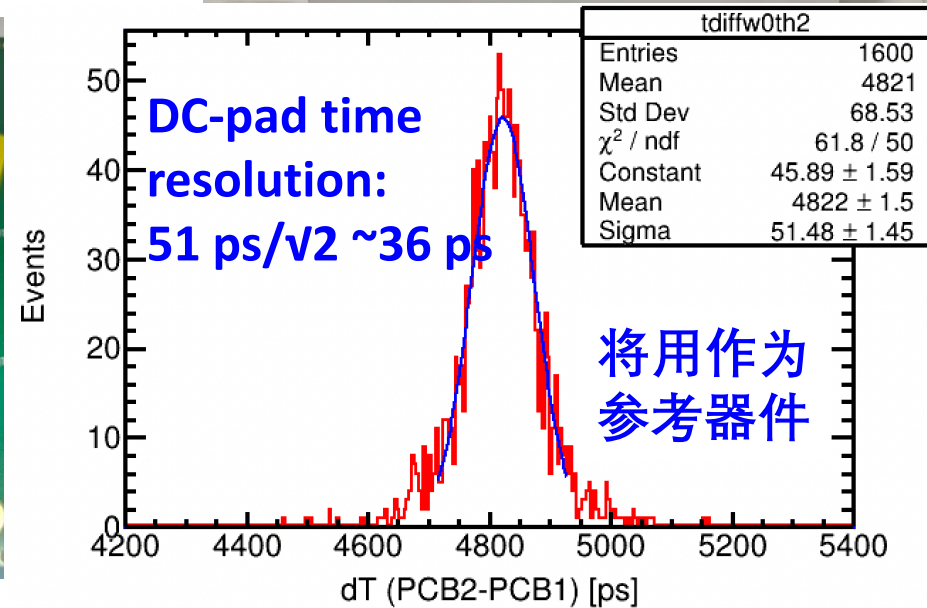
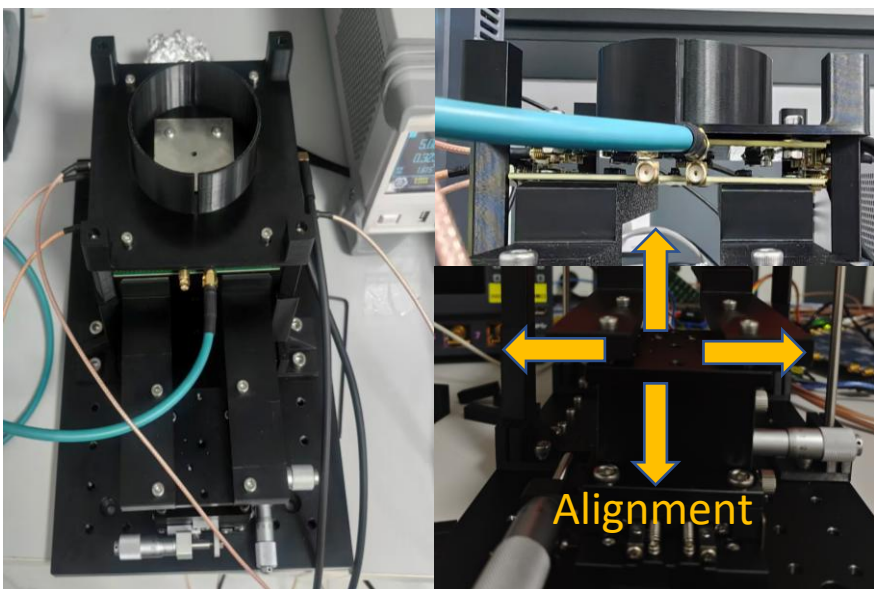
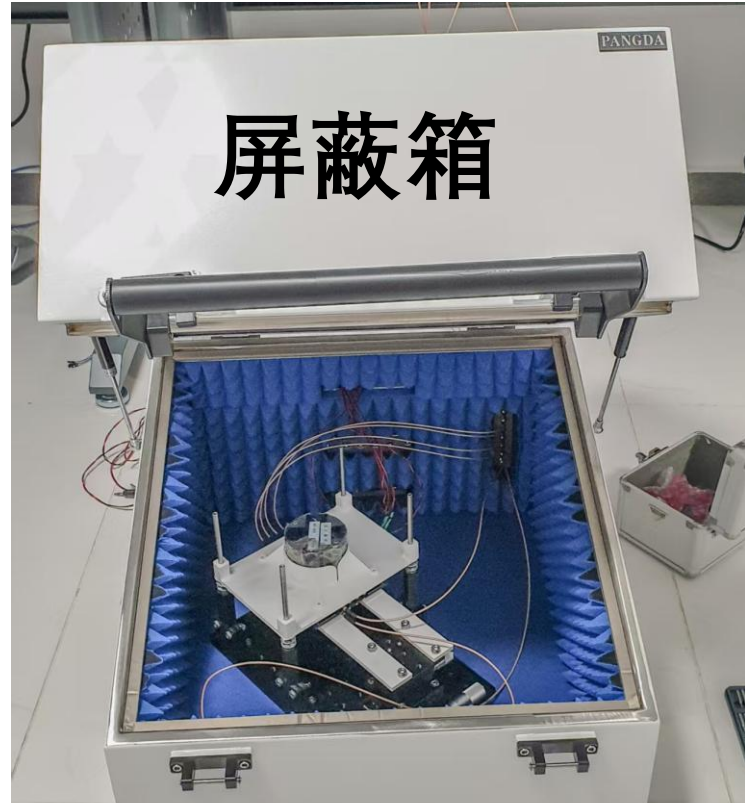
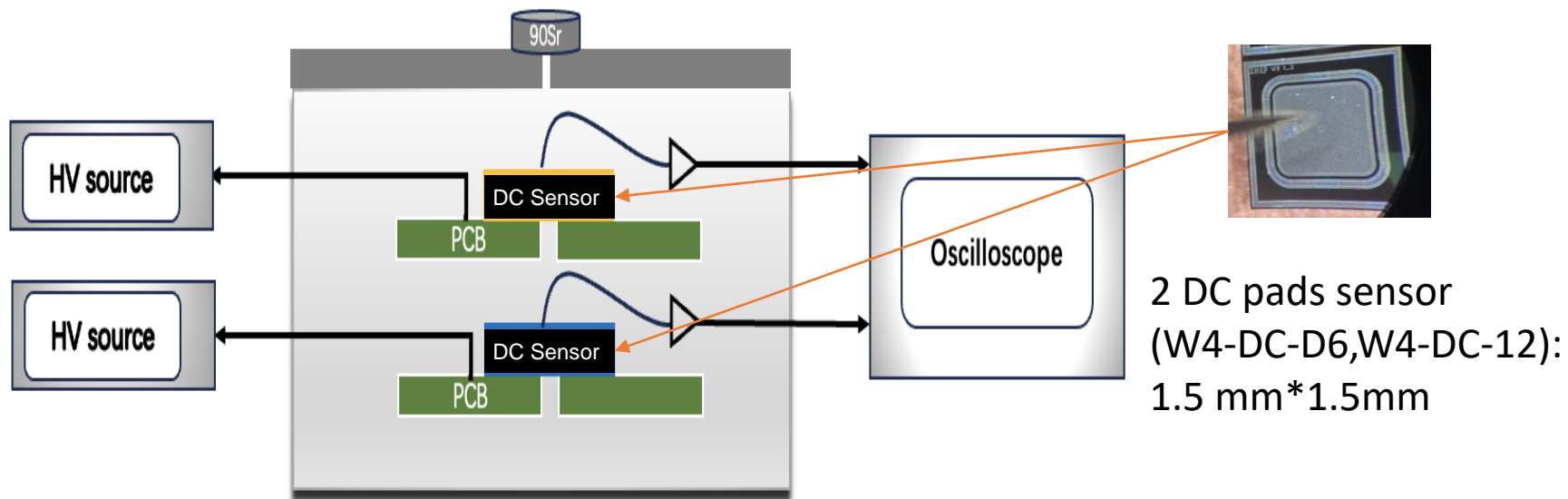
# 传感器表征

- 已对1号、3号和4号晶圆进行测试。
- 完成了I-V、C-V特性测量以及利用β源与激光TCT系统，完成空间与时间性能的测试。

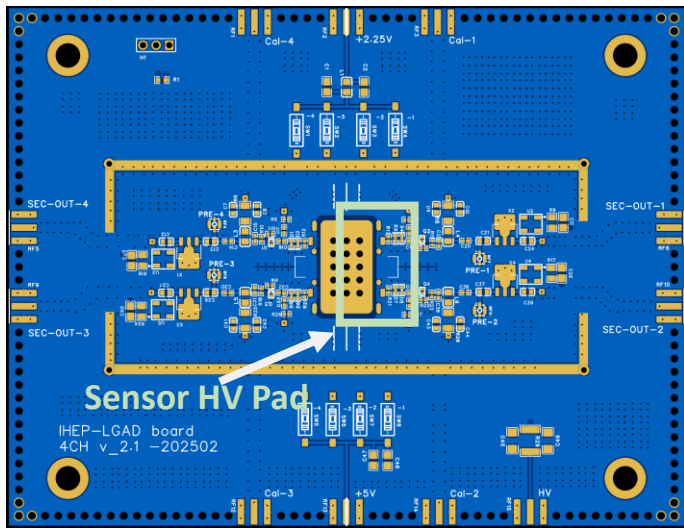
Wafer	EPI Thickness	N <sup>+</sup> Dose
1	50μm	10p
2	50μm	10p
3	50μm	0.01p
7	80μm	10p
8	80μm	0.01p
4	50μm	1p, 0.1p
9	80μm	1p, 0.1p



# Sr-90 $\beta$ 源测试装置



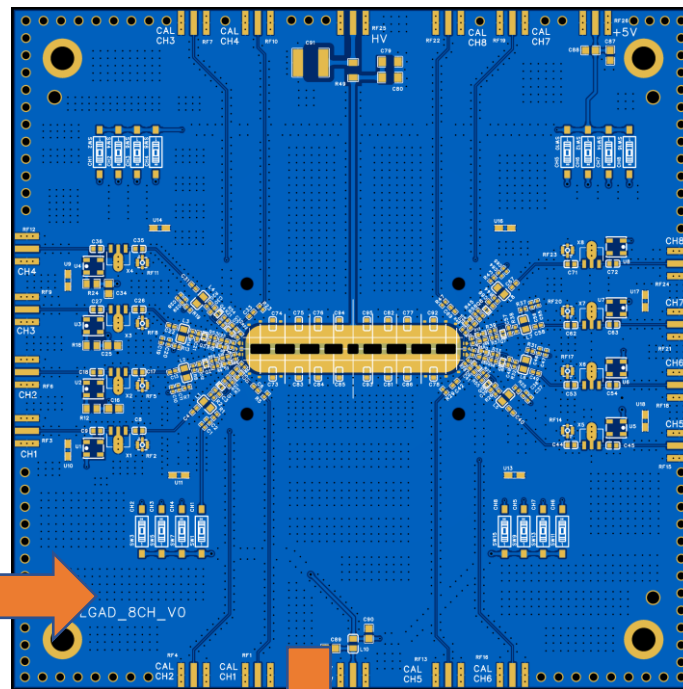
# AC-LGAD前置放大板优化



10cm x 13cm

## V1: 4通道LGAD前置放大板

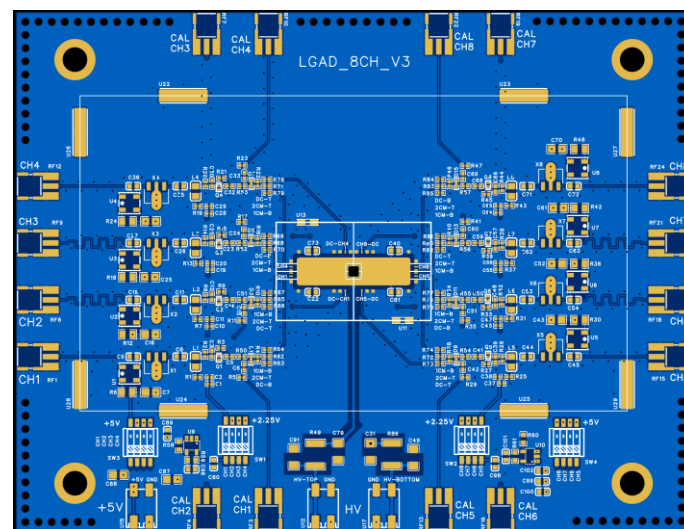
- 为LGAD传感器提供高压偏置。
- 4个信号读出通道
- 每通道约100倍放大



13cm x 13cm

## V2: 8通道LGAD前置放大板:

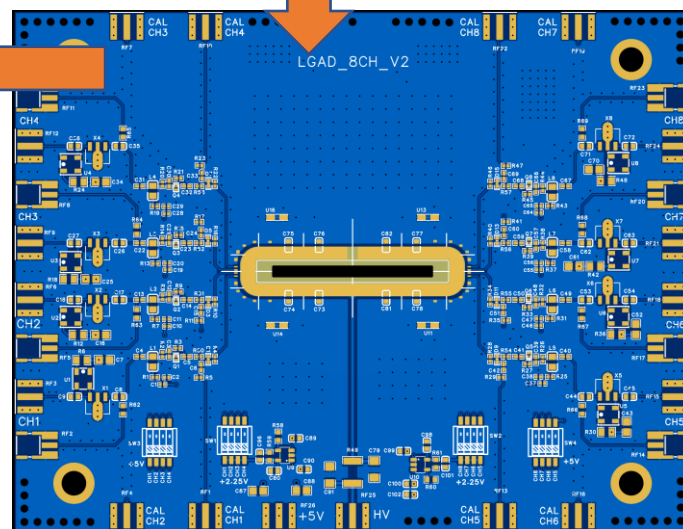
- 增加通道数量
- 扩展高压焊盘以更好兼容条形传感器
- 优化带开槽的高压焊盘几何结构, 以提高粒子探测效率



10cm x 13cm

## V4: 8通道双面LGAD前置放大板:

- 采用**双面设计**以支持不同类型的LGAD (像素型和条形)
- 优化走线设计, 所有8个通道采用**等长走线**
- 将电路板厚度减小至约5 mm



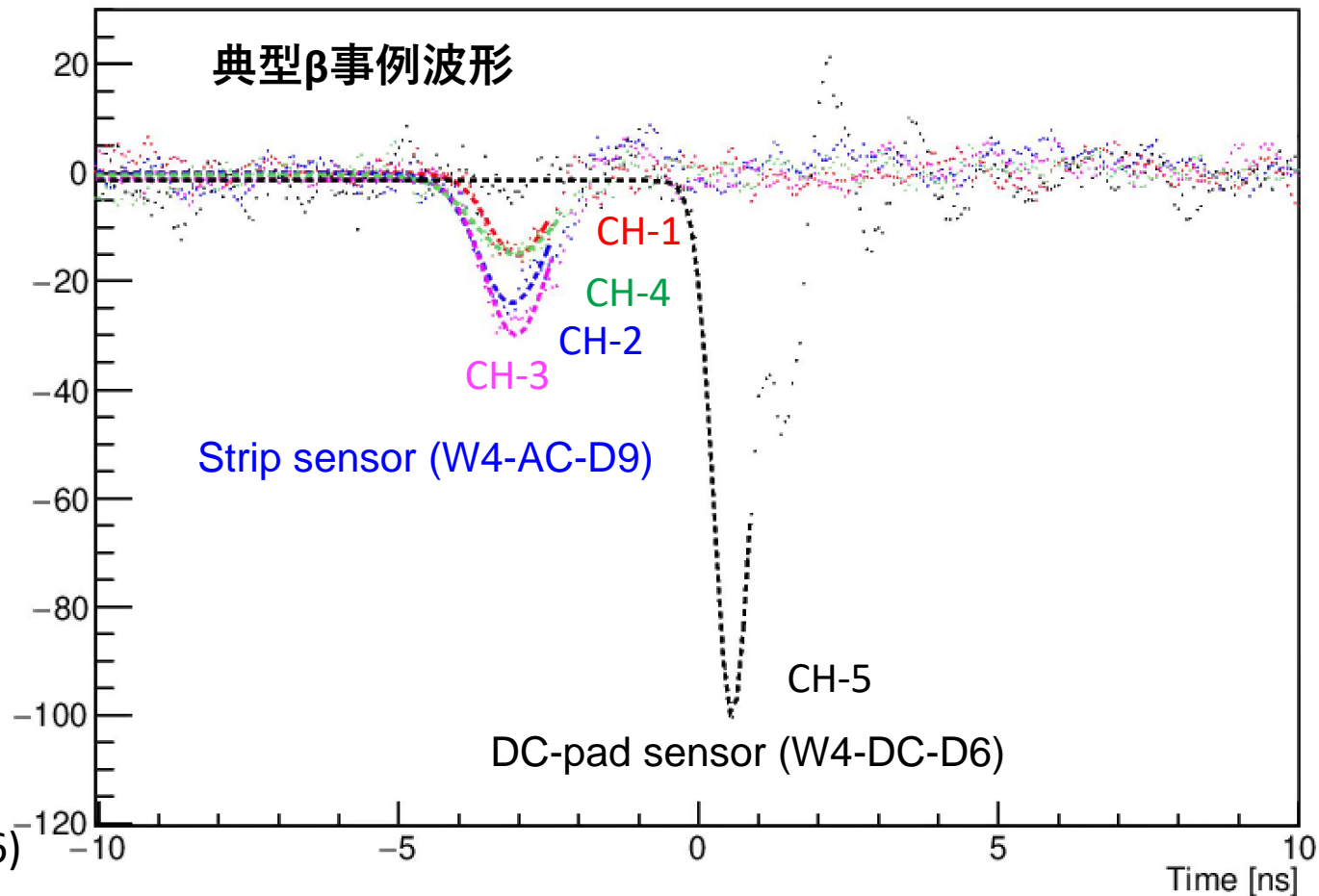
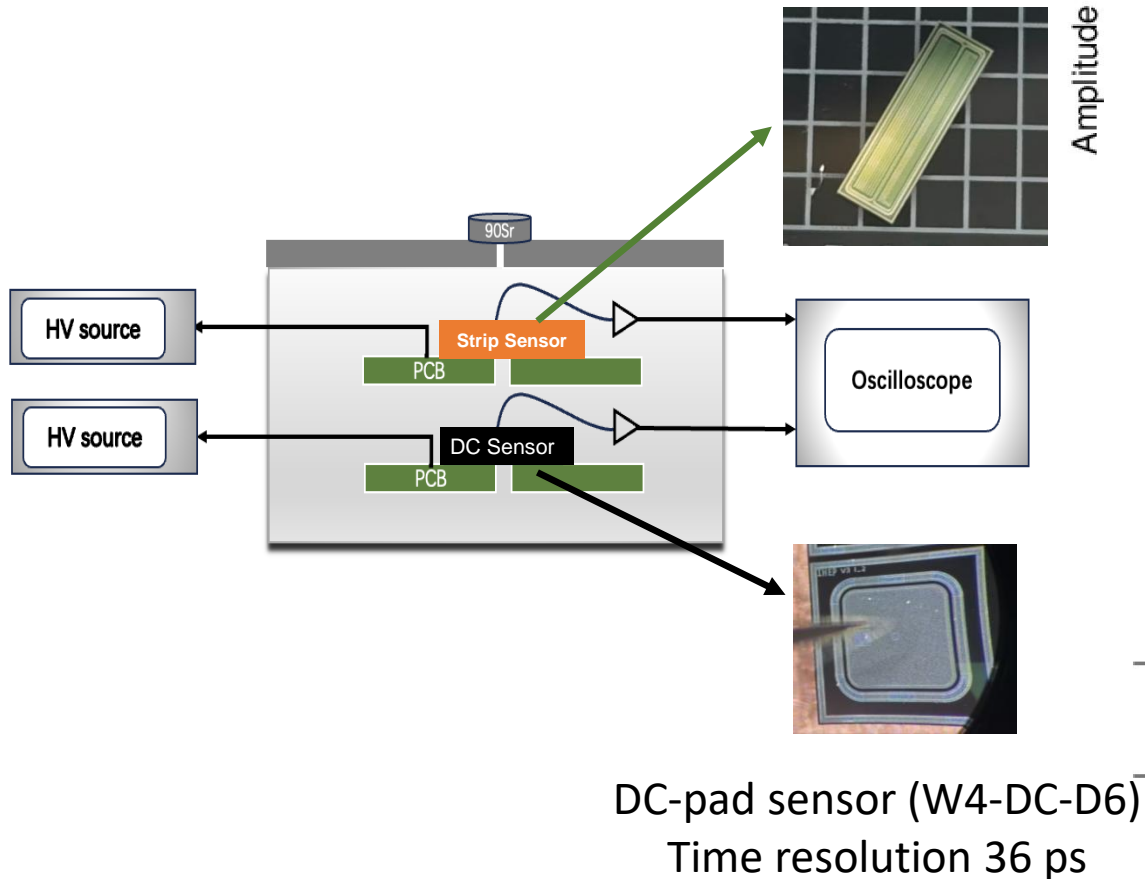
10cm x 13cm

## V3: 8通道LGAD前置放大板

- 减小电路板尺寸以利于集成
- 简化电源连接器以方便布线
- 优化高压焊盘开槽几何结构, 进一步提升粒子探测效率

# 基于 $^{90}\text{Sr}$ $\beta$ 源的传感器性能测量

DUT Strip sensor (W4-AC-D9, 2 cm)

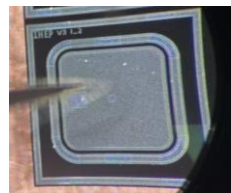


# 条形传感器时间分辨率( $\beta$ -Source Test)

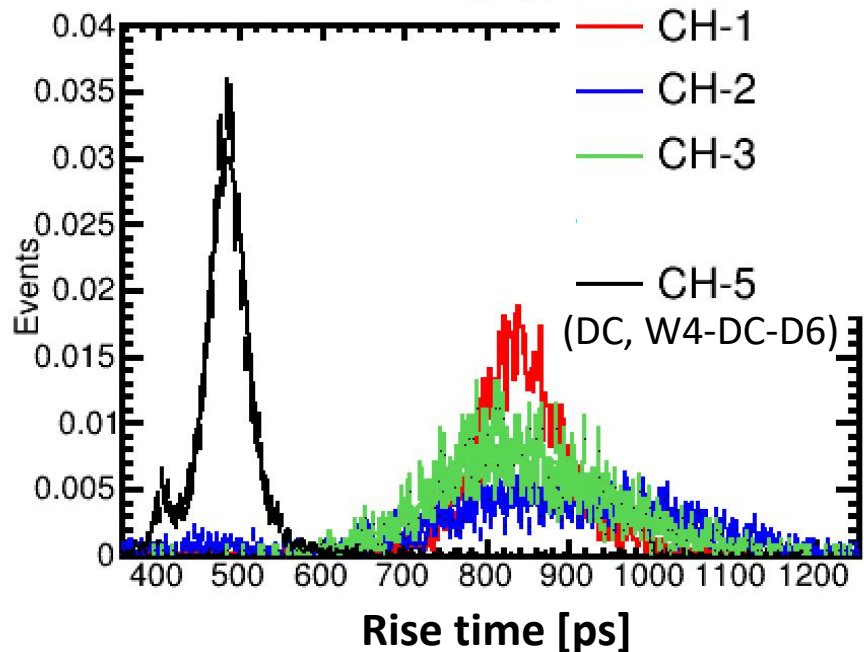
DUT sensor (AC-LGAD)

Ref sensor (DC)

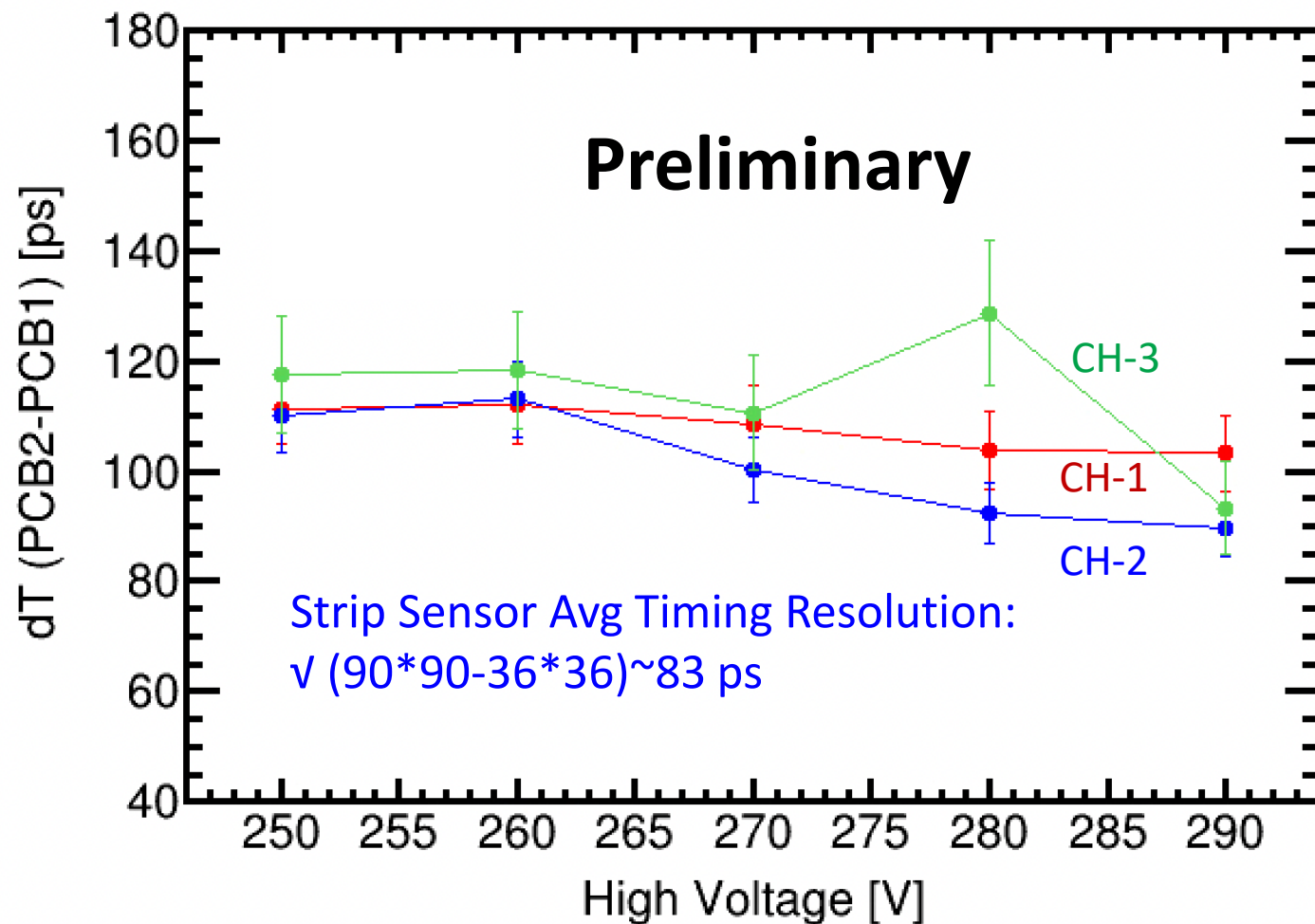
CH-1  
CH-2  
CH-3  
CH-4



CH-5



W4-AC-D9, 条长2 cm, 条间距 100 $\mu$ m, 电极宽度50 $\mu$ m



- 条形传感器的信号上升时间显著长于面型传感器。
- 该条形传感器 (长2 cm, 间距100  $\mu$ m, 电极宽度50  $\mu$ m) 实现了约83 ps的时间分辨率。

激光输入口

# 红外激光 (1064 nm) 测试装置

聚焦透镜

z- 位移台

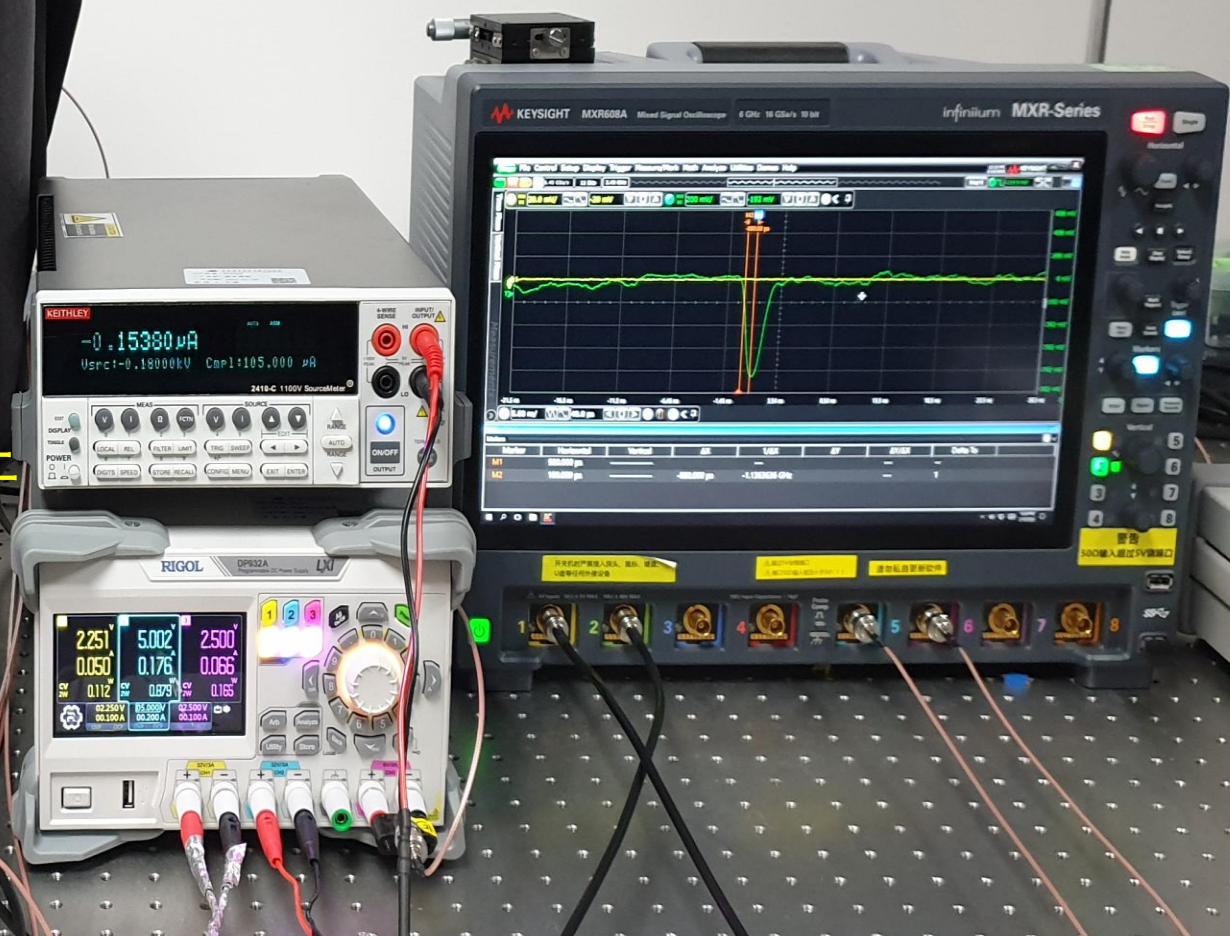
滤光片

待测器件

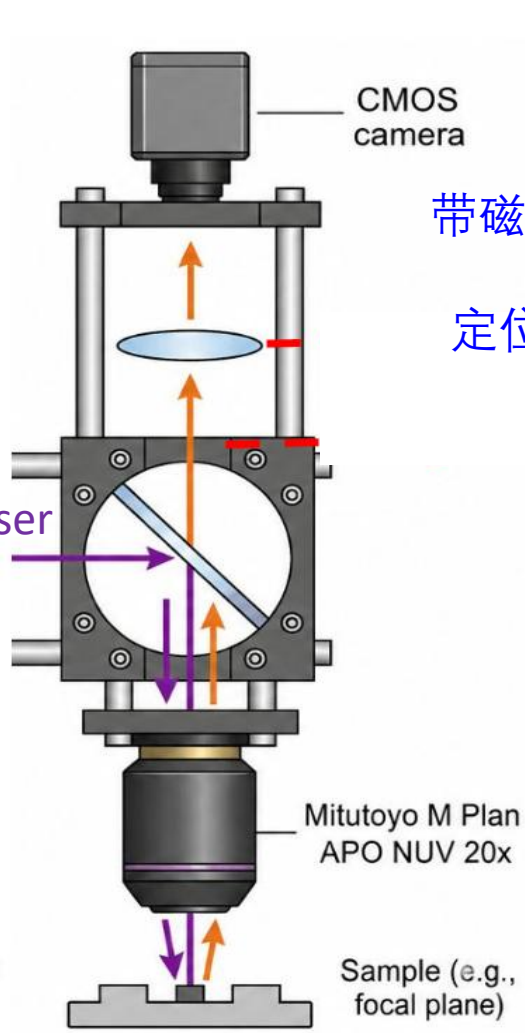
红外CMOS 相机

y-

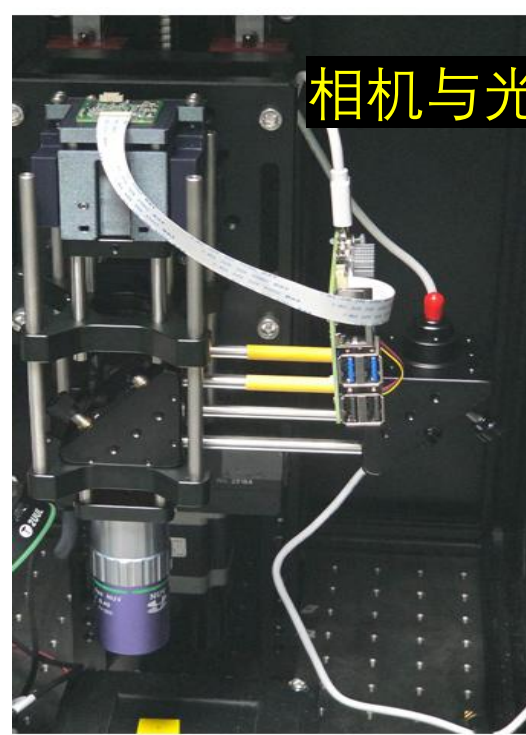
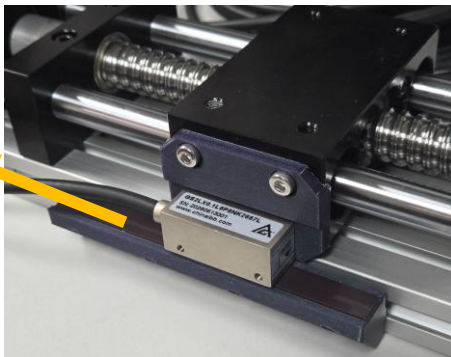
x-



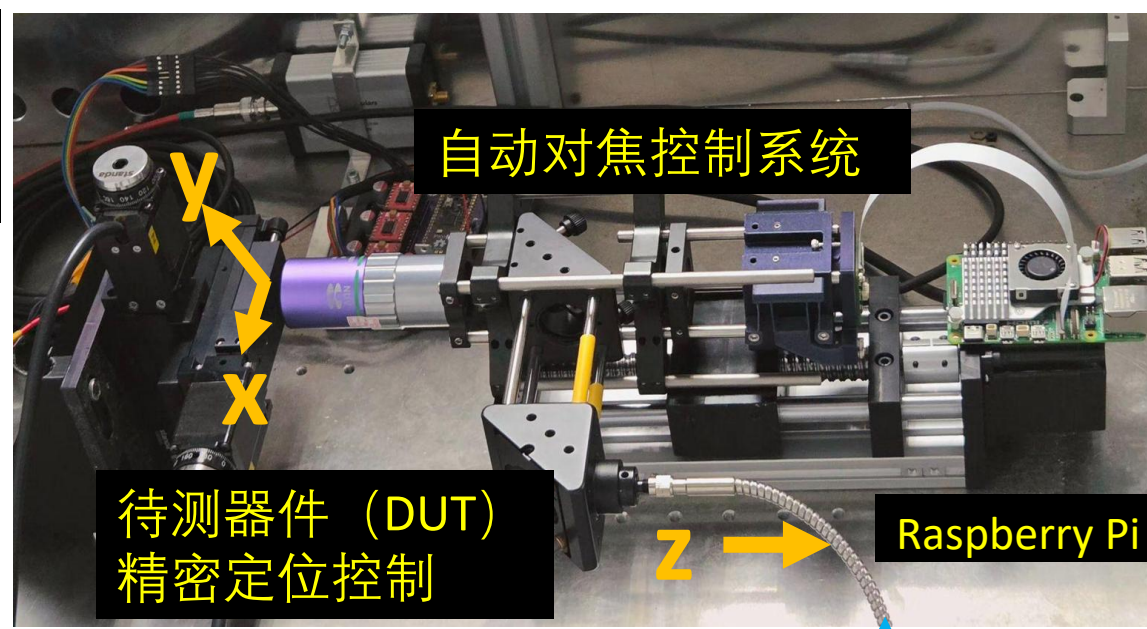
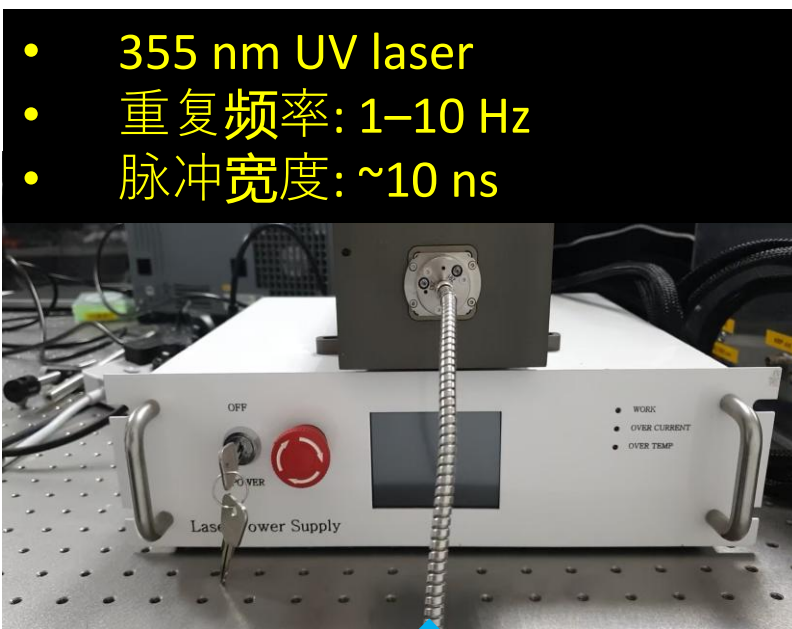
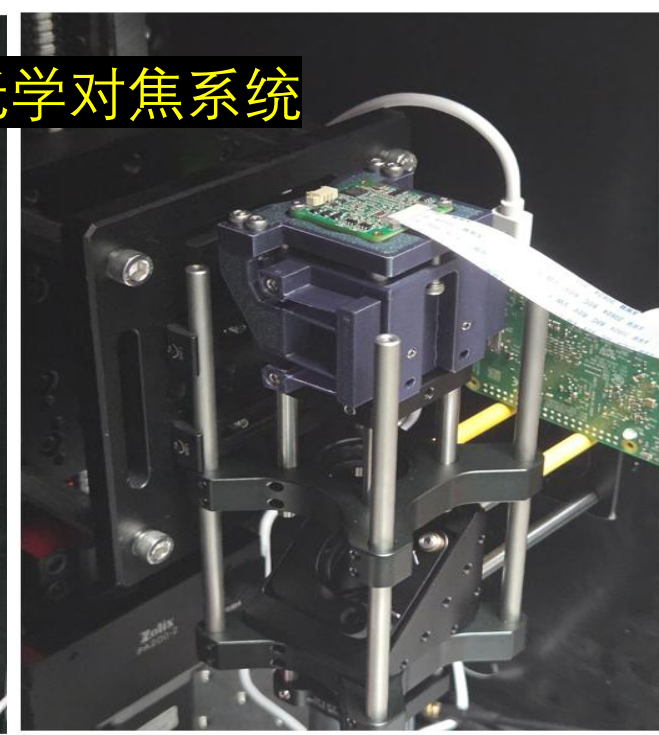
- 除红外测试系统外，还开发了专用于碳化硅 (SiC) 传感器的紫外激光测试平台。  
硅与碳化硅传感器的研发共享统一的研发框架，共用测试基础设施、前端电子学及系统集成资源



带磁编码器反馈的  
步进电机  
定位精度  $< 0.1 \mu\text{m}$

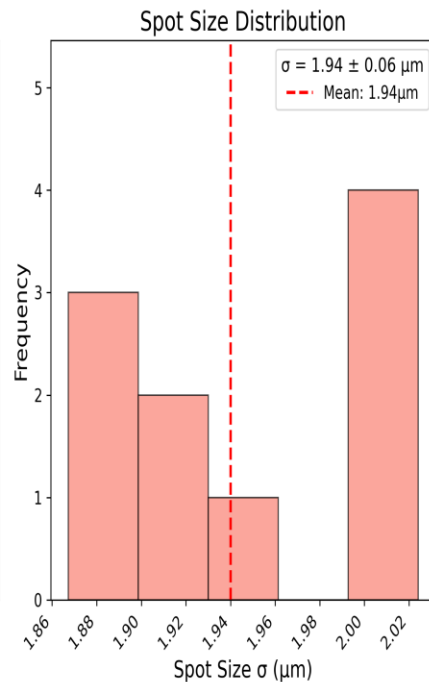
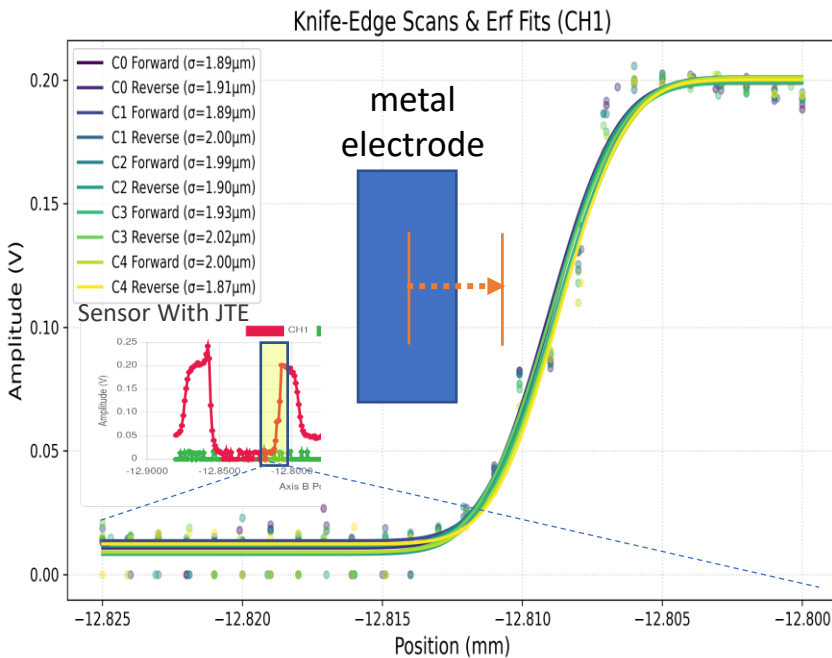


相机与光学对焦系统

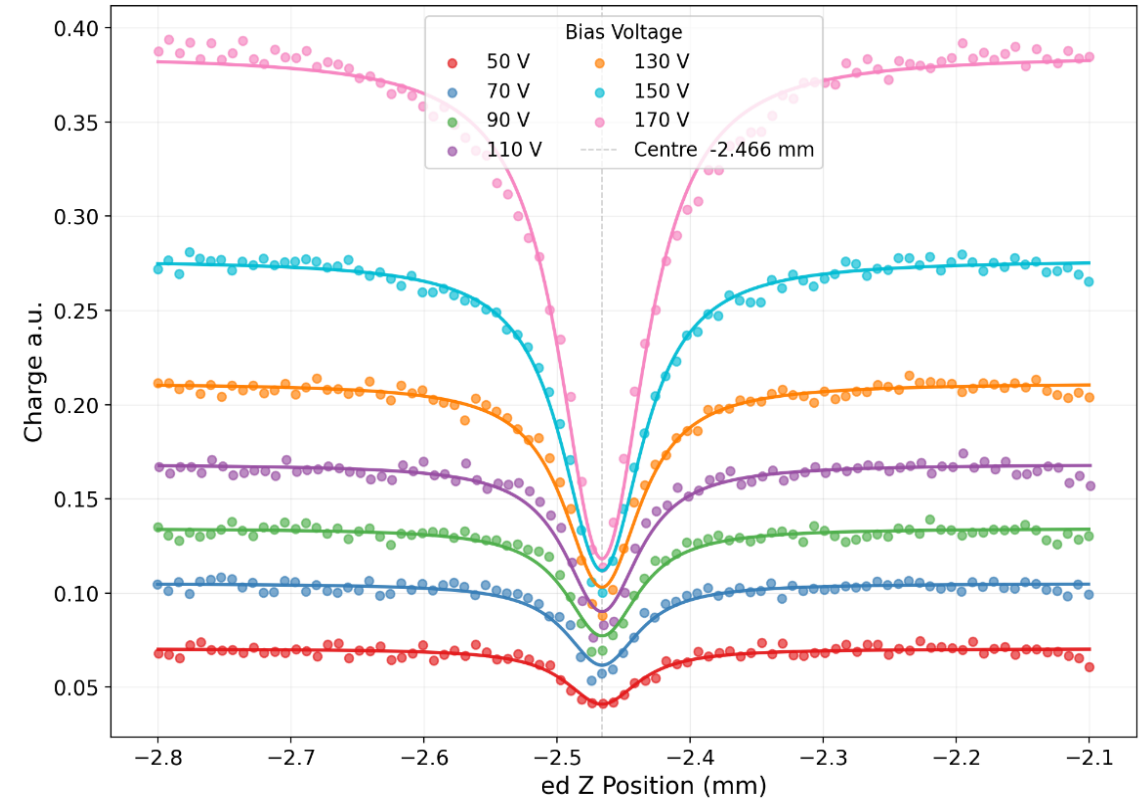


# 光斑尺寸最小化

- 采用两种独立方法进行交叉验证:
  1. 增益抑制效应 → 扫描Z轴位置
  2. 刀刃法 → 在每个Z位置沿电极边缘进行扫描



## Gain suppression effect

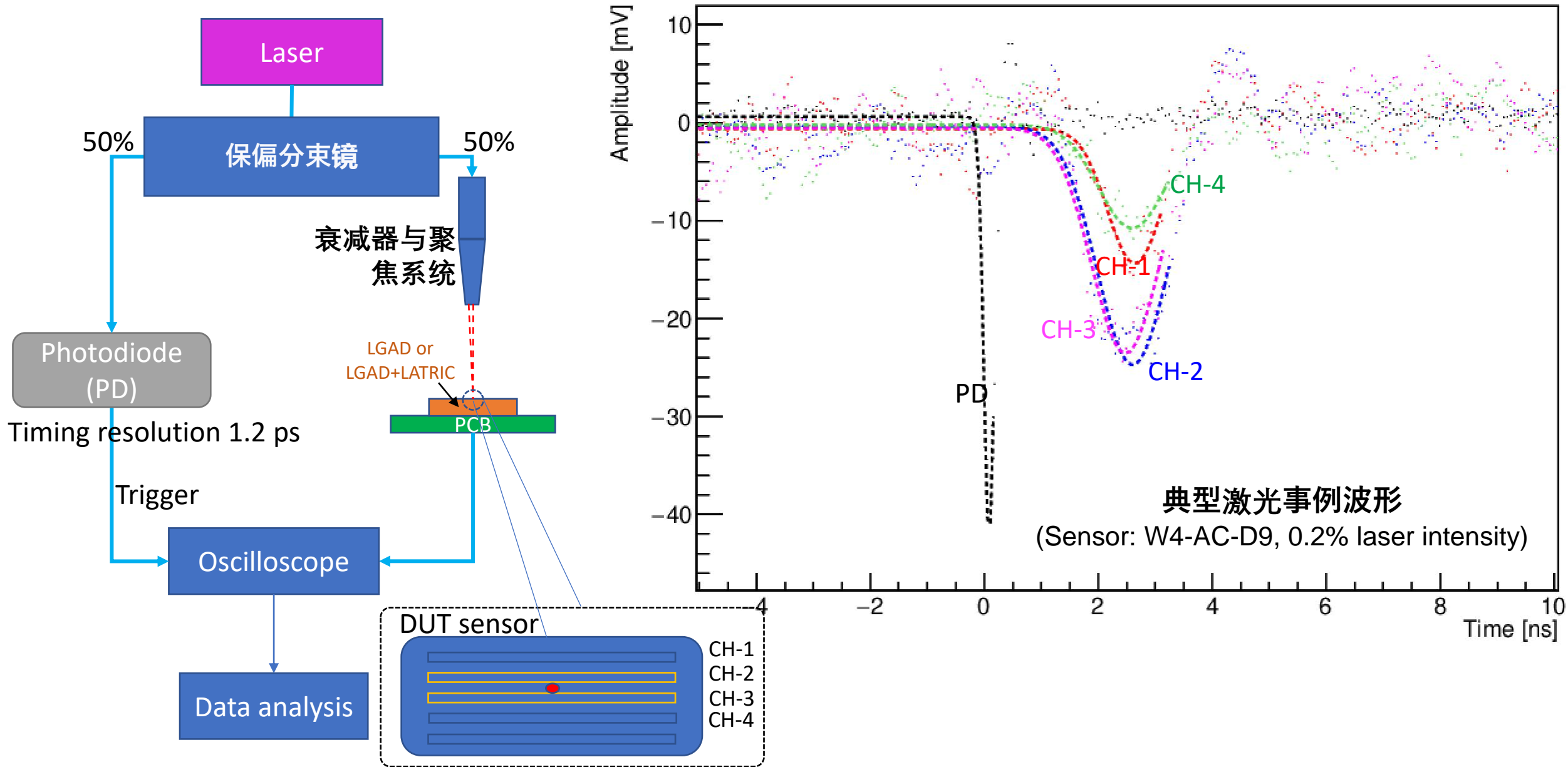


$$S(z) = S_{max} \exp\left(-\frac{A}{w_0^2 \left[1 + \left(\frac{z - z_0}{z_R}\right)^2\right]}\right)$$

- $w_0$ : The beam waist (minimum radius).
- $z_0$ : The focal point position.
- $z_R$ : The Rayleigh length.

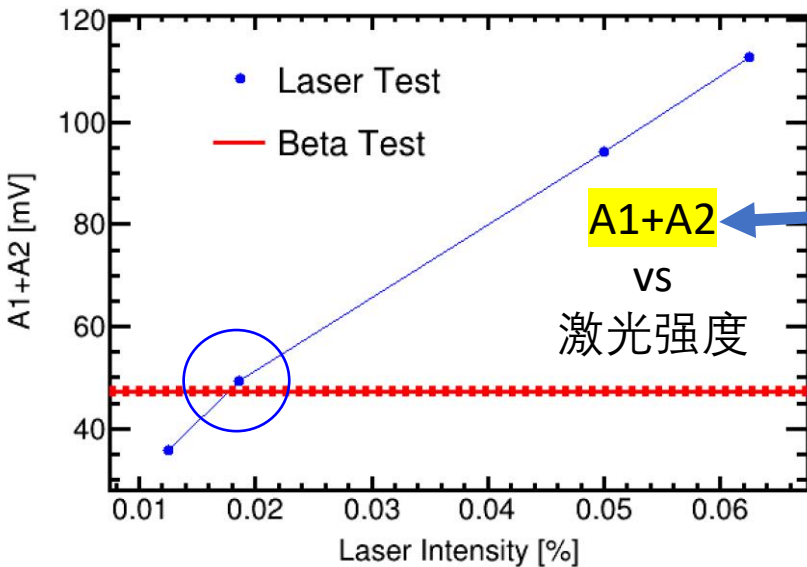
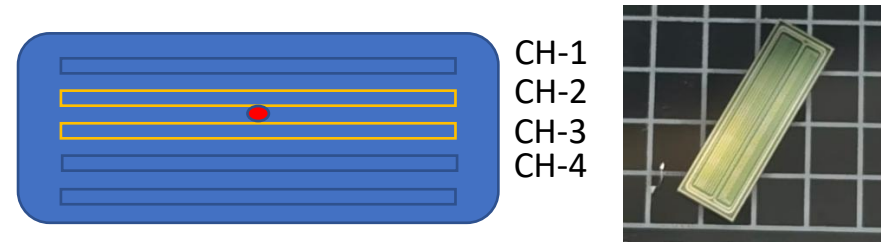
确认可调式出光斑半径:  $< 3\mu\text{m}$

# 基于红外激光的传感器性能测量

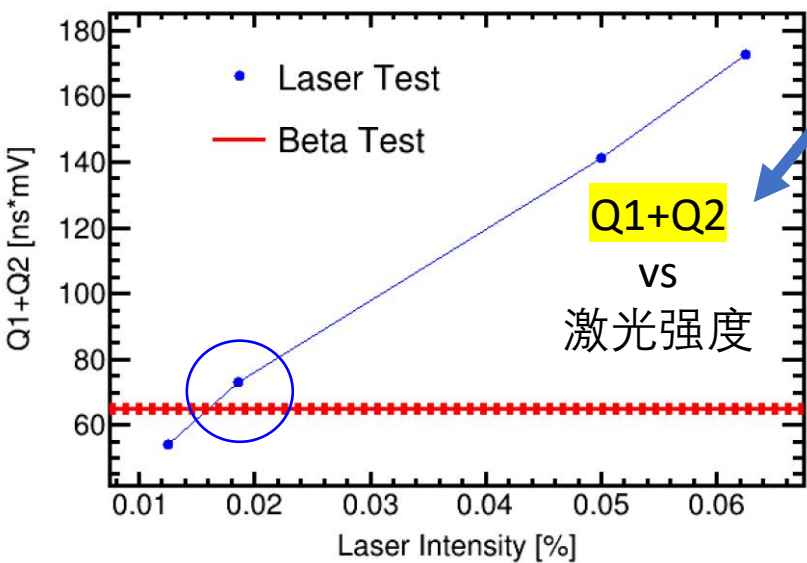


# Beta-Equivalent Laser Intensity Tuning

Strip sensor (W4-AC-D9, 2 cm)

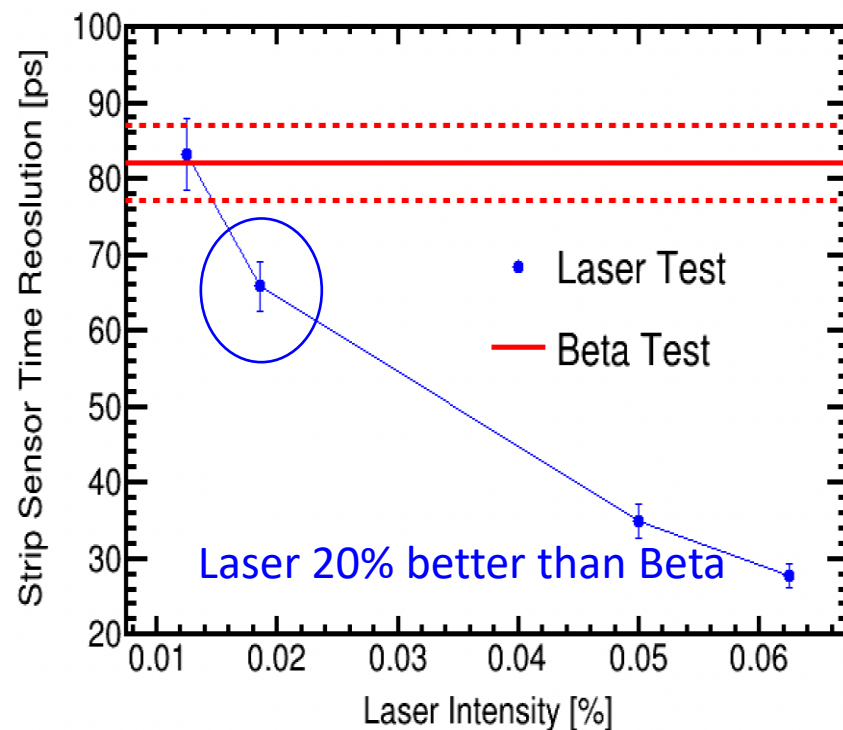


A1和A2分别为seed strip (最大幅值) 和第二微条的波形幅值。



Q1和Q2为对应波形的积分电荷 (负极性)

0.02%的激光强度在幅值和积分电荷上均与最小电离粒子 (MIP) 响应相匹配。

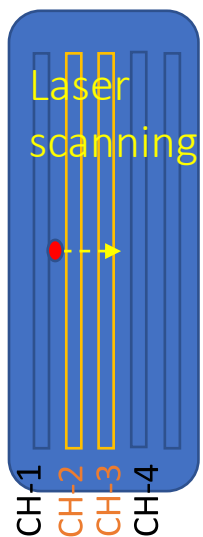


通过激光测试获得的条形传感器 (W4-AC-D9, 2 cm) 时间分辨率约为65 ps, 比β源测试 (约80 ps) 提升了20%, 这是由于激光测量中不存在dE/dx的朗道涨落

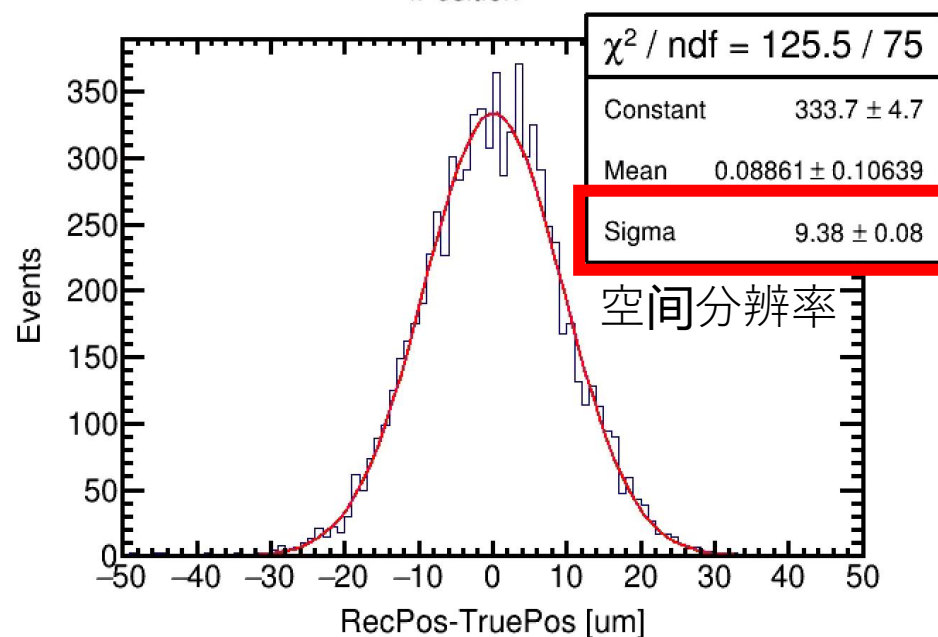
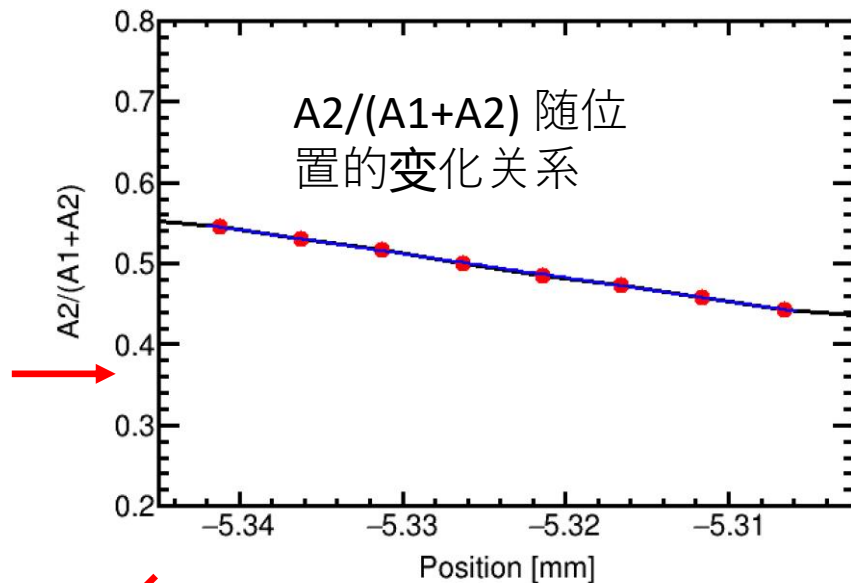
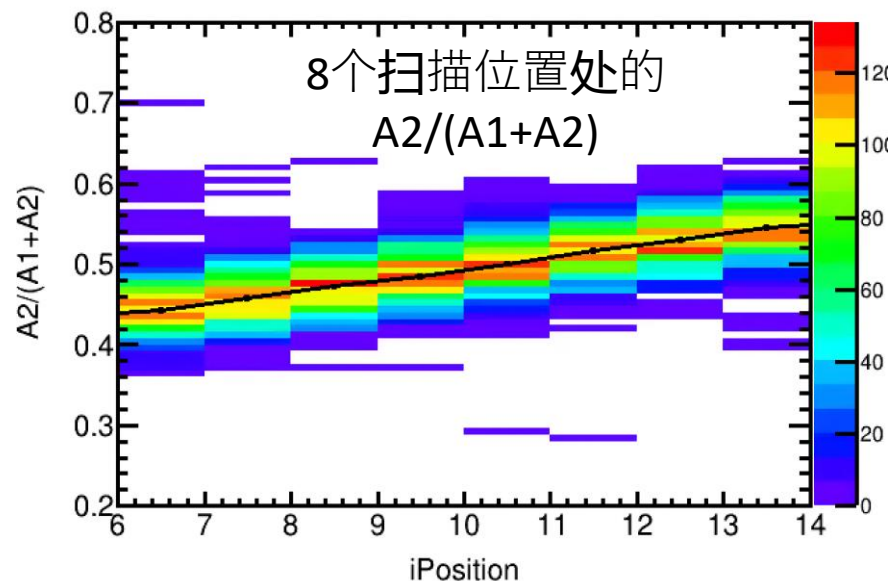
# 等效MIP激光 (0.02%强度) 下条形传感器的空间分辨率

A1和A2分别为seed strip (最大幅值) 和第二微条的波形幅值。

扫描步长为5  $\mu\text{m}$   
每步采集1000个波形



Strip sensor (W4-AC-D9, 2 cm):  
Open window of 50  $\mu\text{m}$  between 2 strips.

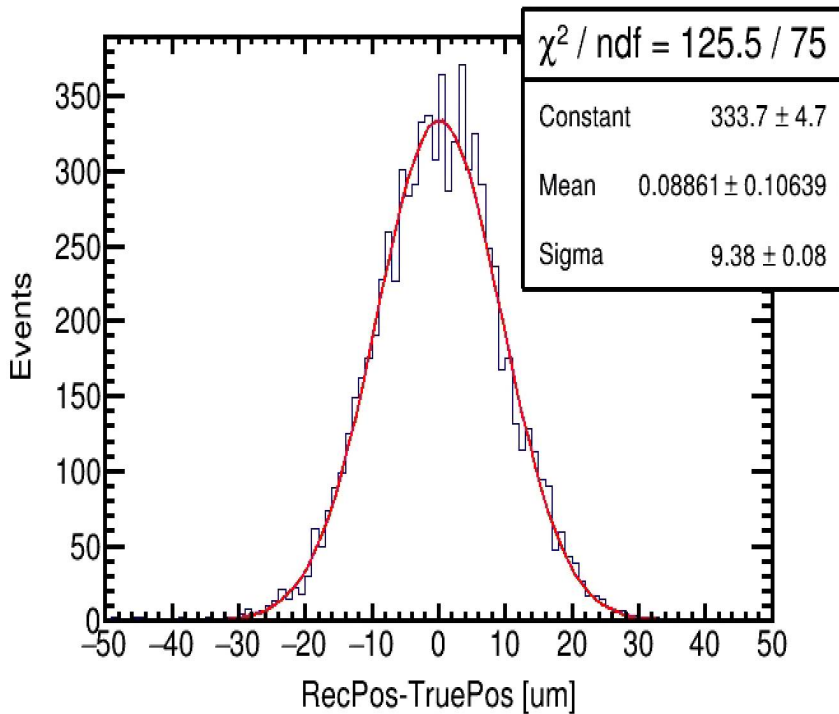


最新流片优化的n<sup>+</sup>条形传感器  
(W4-AC-D9: 长2 cm, 间距100  $\mu\text{m}$ , 电极宽度50  $\mu\text{m}$ , n<sup>+</sup>注入剂量为0.1 p)

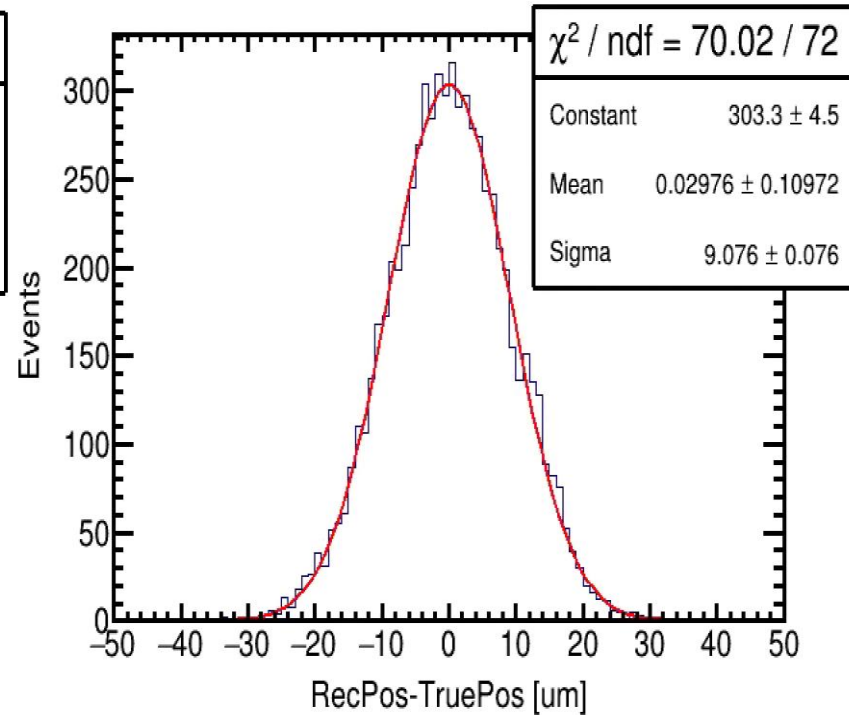
实现了9.4  $\mu\text{m}$ 的空间分辨率。

# 不同estimator的传感器空间分辨率

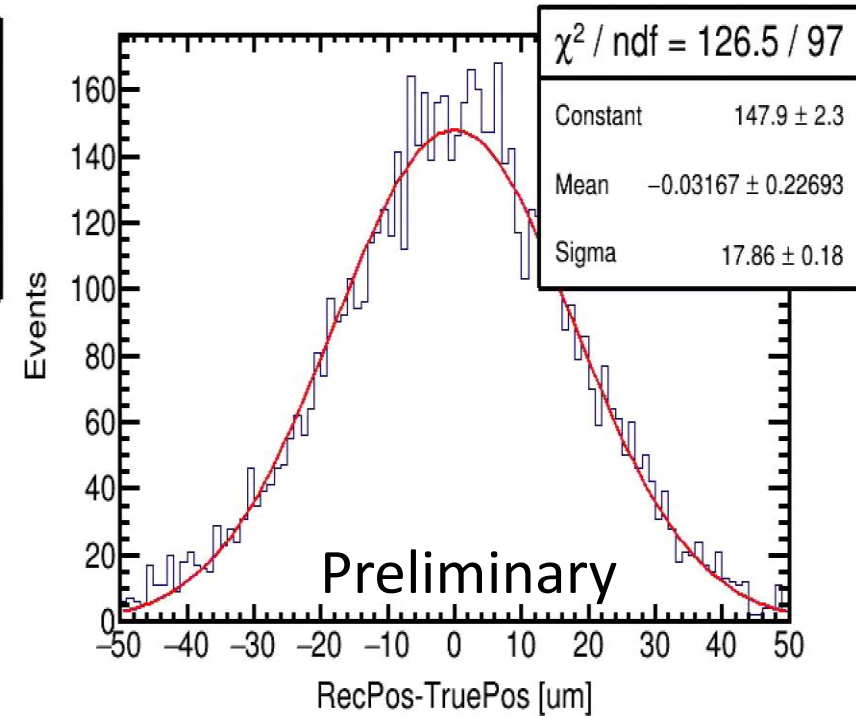
1) 最大幅值



2) 积分电荷



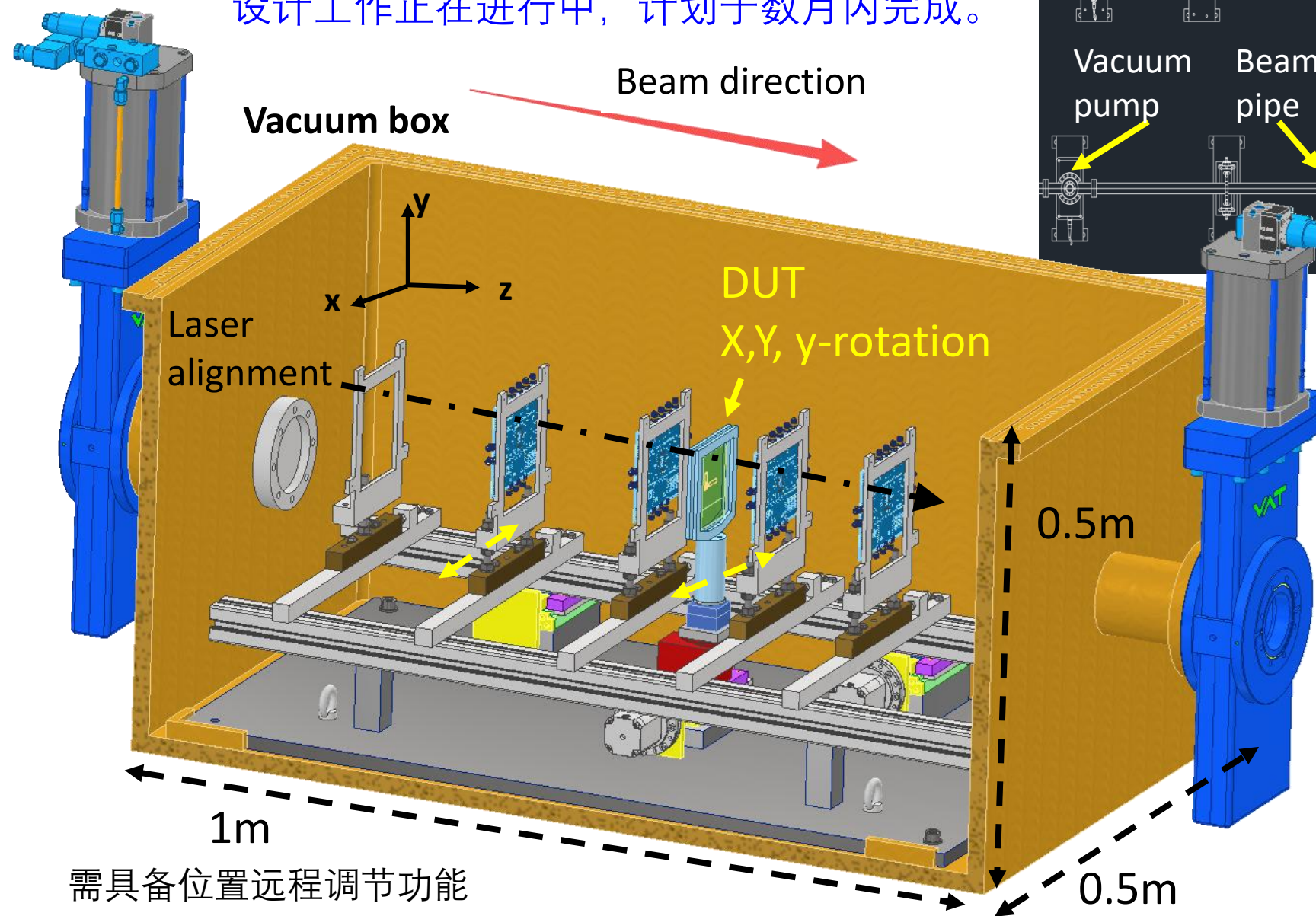
3) 过阈时间 (TOT)



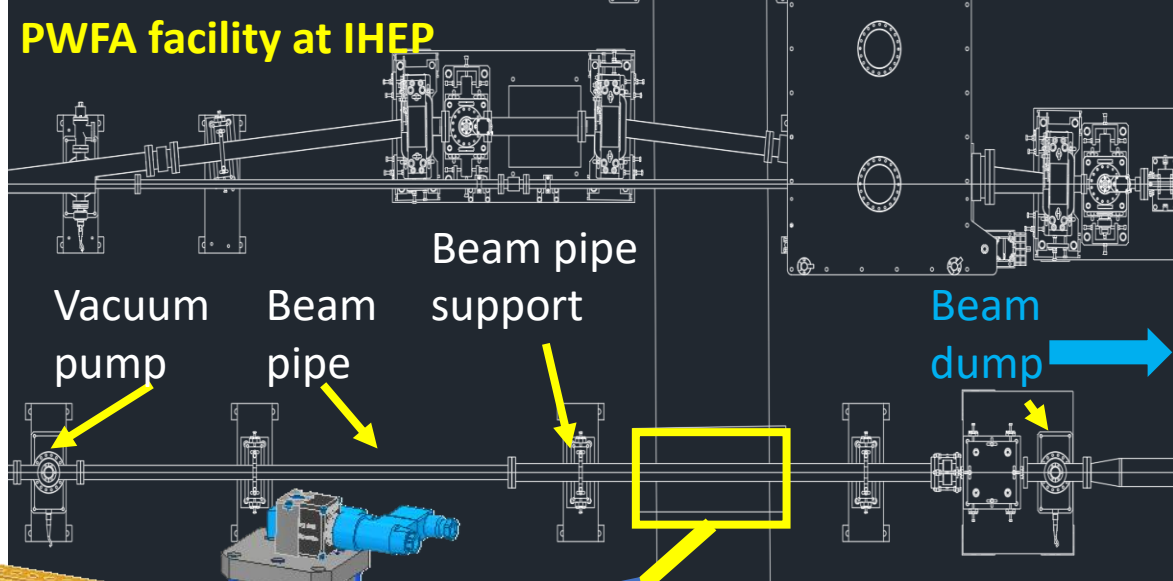
在100  $\mu\text{m}$ 条间距下，仅利用LATRIC的TOT信息来实现优于10  $\mu\text{m}$ 的空间分辨率有较大挑战，且灵活性有限。

# 束流望远镜

设计工作正在进行中，计划于数月内完成。



需具备位置远程调节功能



**目的:** 在开展高能束流测试前，支持初步的束流试验与系统评估（如数据采集系统DAQ）

**地点:** 高能所PWFA设施的beam dump area .

**电子束能量:** ~2 GeV

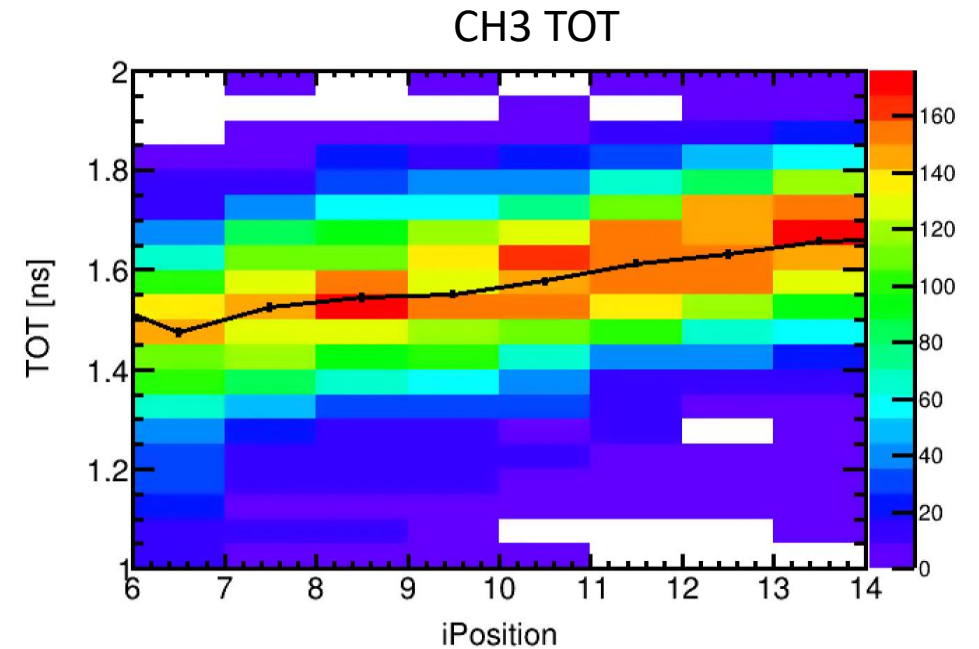
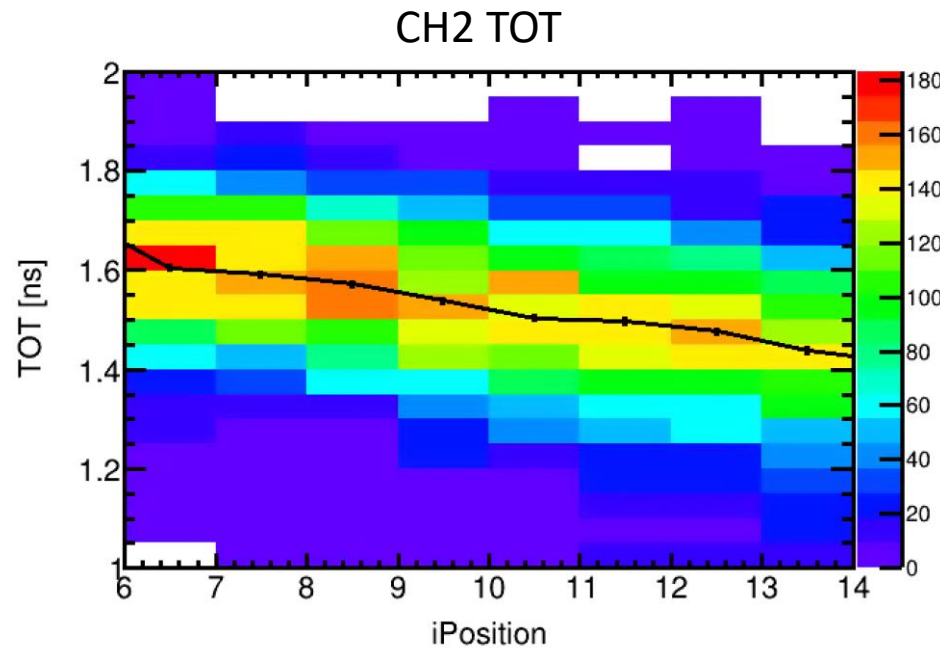
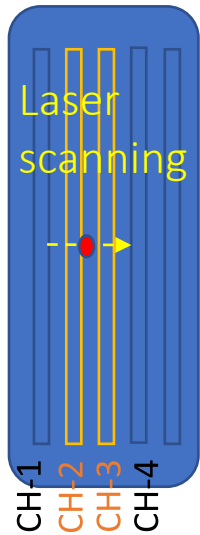
# 总结

- 正全力推进AC-LGAD及其专用读出芯片LATRIC的研发工作。
- 利用激光与 $\beta$ 源开展了初步的时间与空间分辨率研究。
  - 将激光强度调节至等效 $\beta$ 粒子（MIP）信号。
  - 激光测试测得的时间分辨率为65 ps，与 $\beta$ 源测试结果相近，验证了基于激光测试结果的可靠性。
- 正在建设高能所（IHEP）自主束流测试平台

# Additional Slides

# Sensor Spatial Resolution Measured Using TOT (0.02% laser intensity)

Scanning at 8 positions within the 50  $\mu\text{m}$  open window between CH2 and CH3.

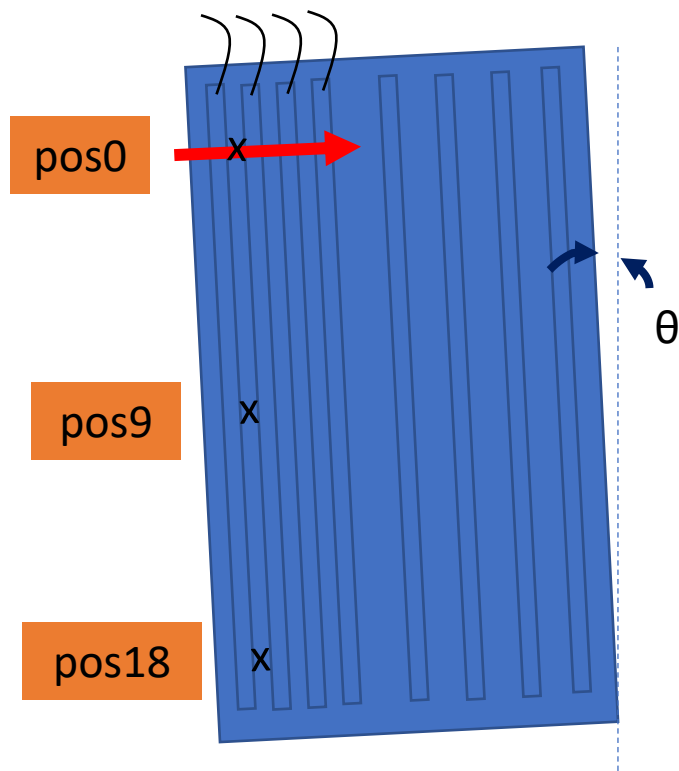


Achieving a spatial resolution below 10  $\mu\text{m}$  using Time Over Threshold (TOT) information (LATRIC) with a 100  $\mu\text{m}$  strip pitch appears to be challenging and may offer limited flexibility.

# W4-AC-D7-2-1 ( $n^+ = 1P$ )

→ Lateral scan (0.005/step)

x Longitudinal scan (3 points)

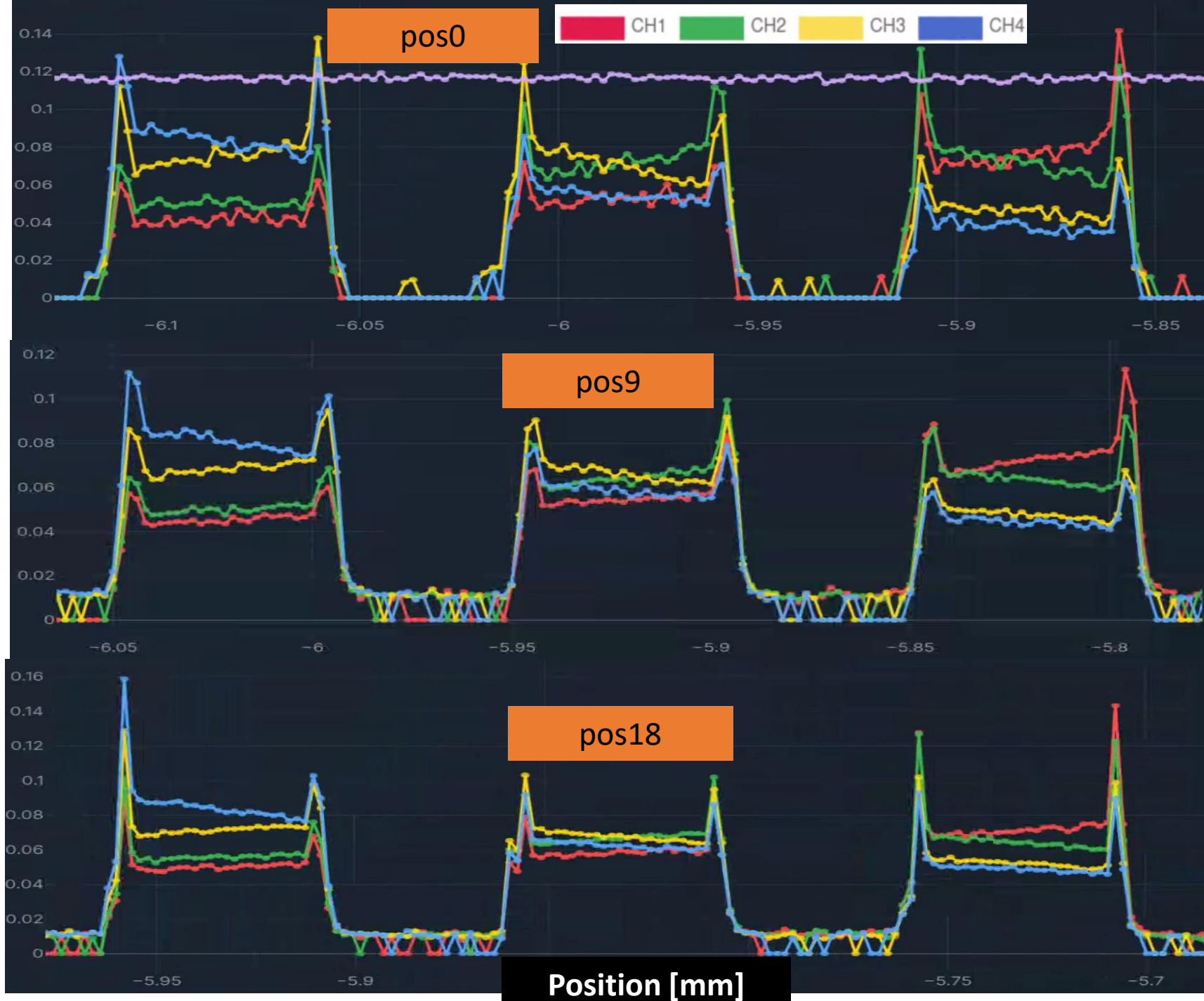


EPI thickness: 50  $\mu\text{m}$

Strip length: 2cm

Pitch: 100  $\mu\text{m}$

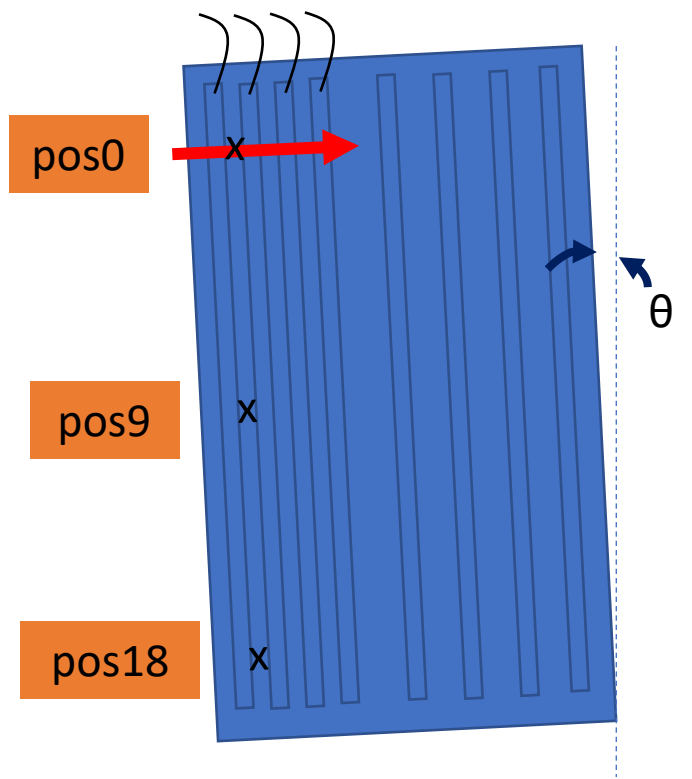
Gap :50  $\mu\text{m}$



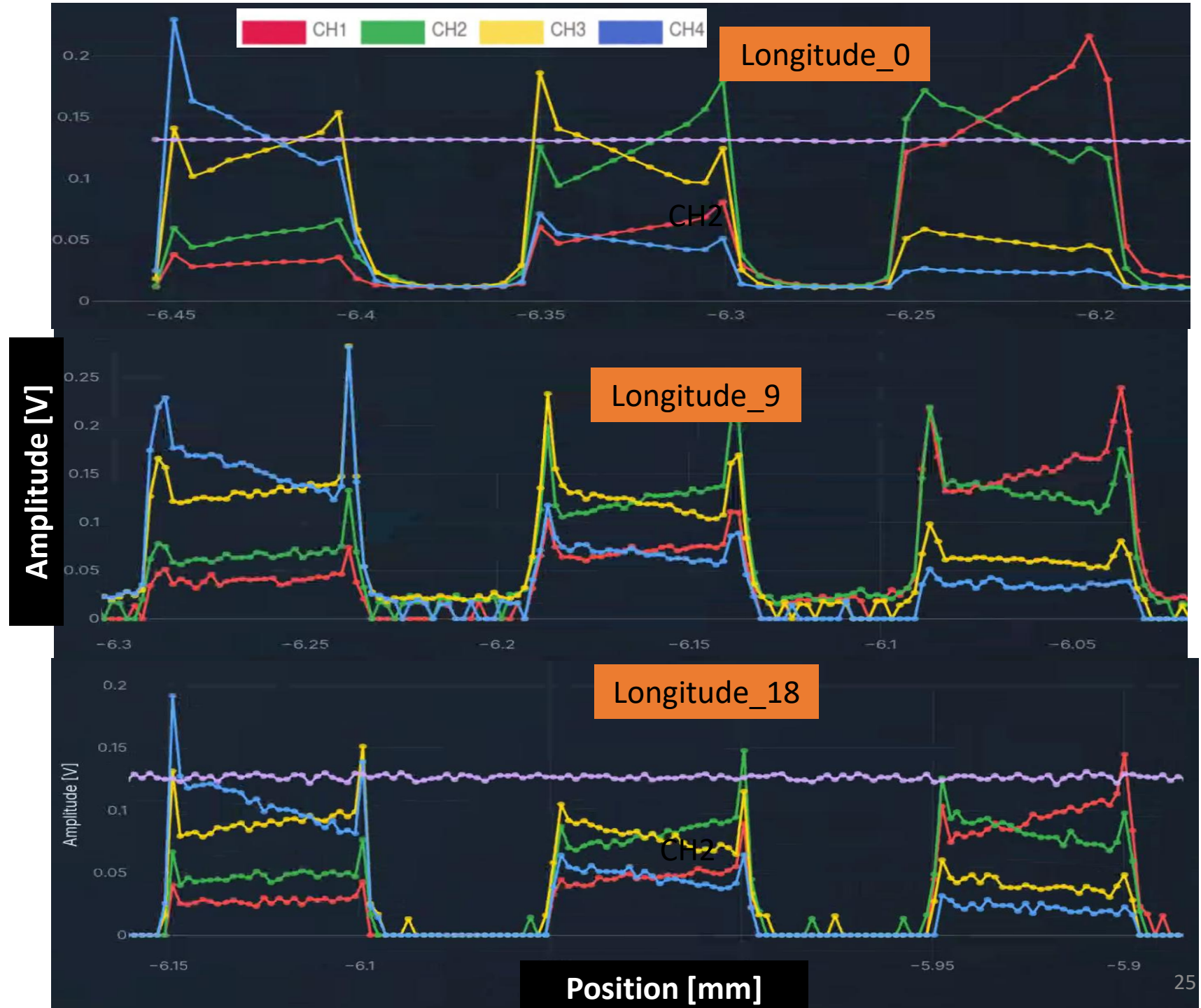
# W4-AC-D9-2-1 ( $n^+ = 0.1P$ )

 Lateral scan (0.005/step)

x Longitudinal scan (3 points)



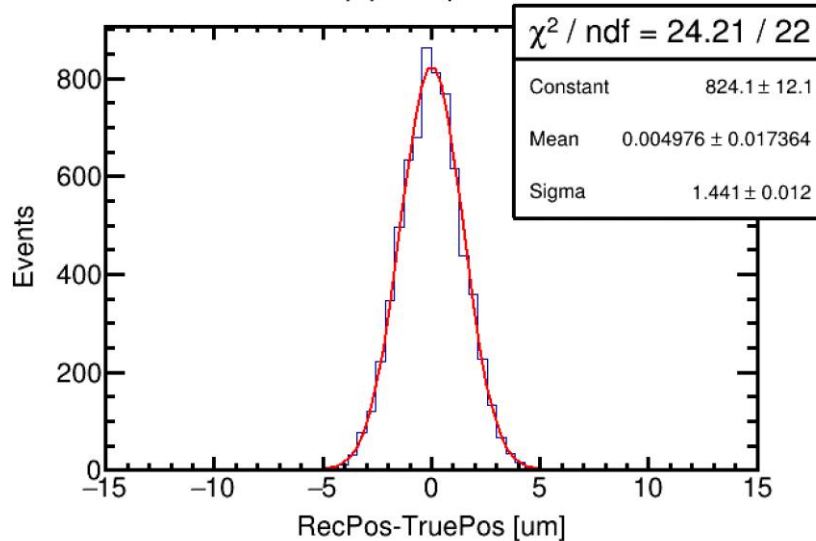
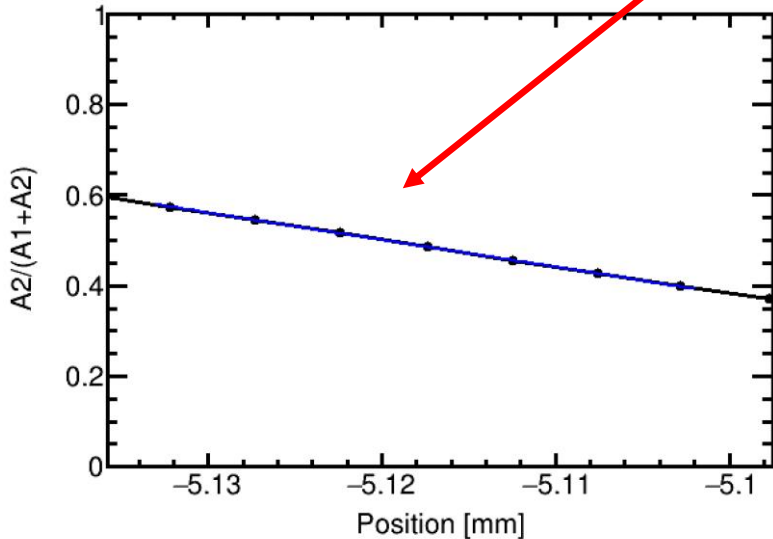
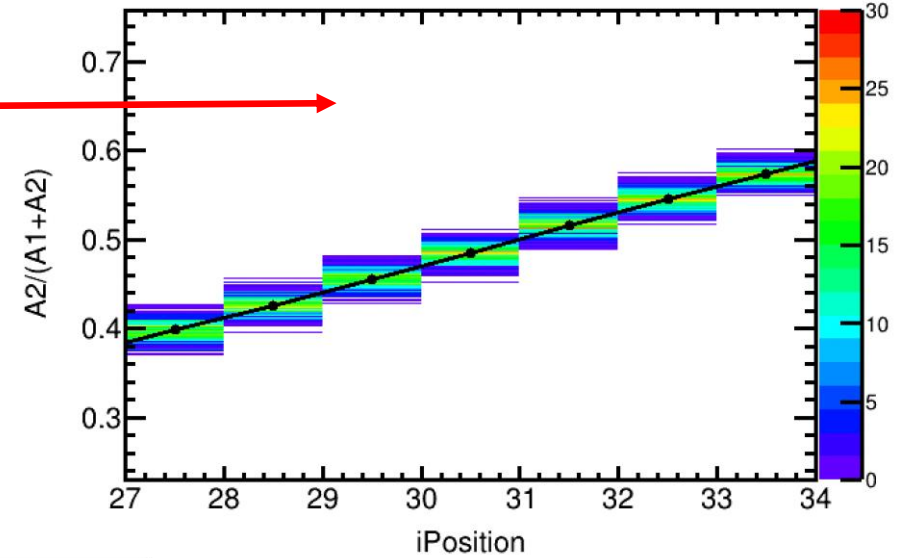
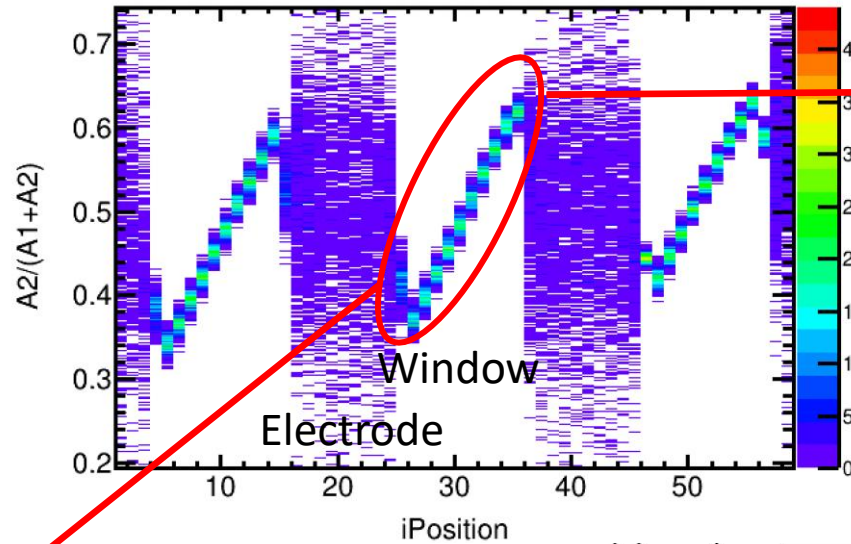
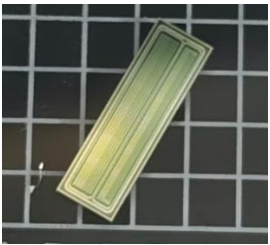
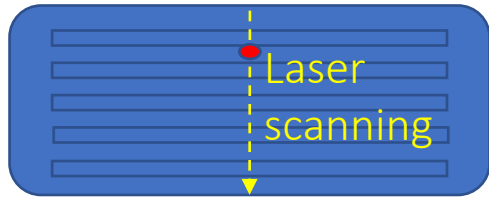
EPI thickness: 50  $\mu$  m  
Strip length: 2cm  
Pitch: 100  $\mu$  m  
Gap :50  $\mu$  m



# Strip Sensor Spatial Resolution (0.2% Laser)

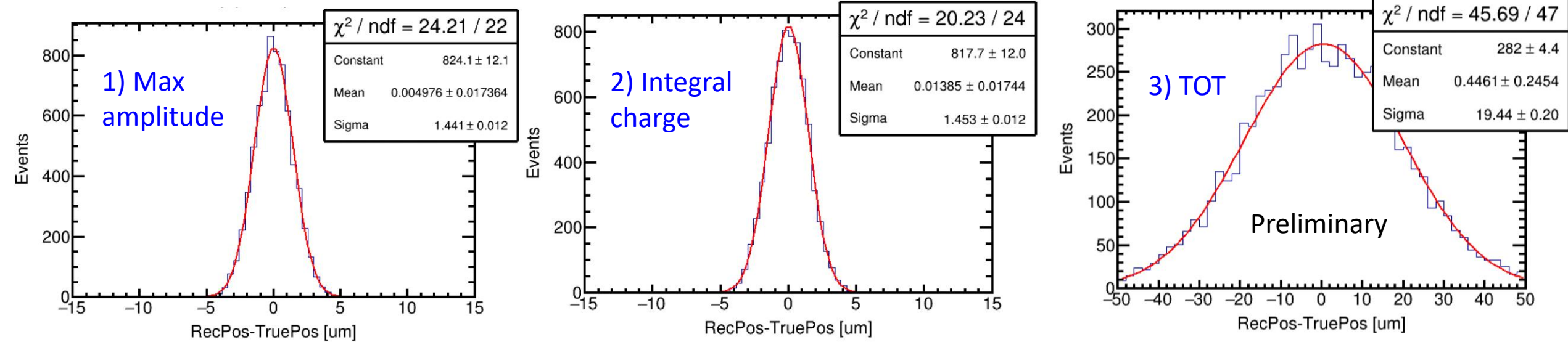
$A_2$  and  $A_1$  are the waveform amplitudes of the seed (maximum amplitude) strip and the second strip, respectively.

DUT sensor



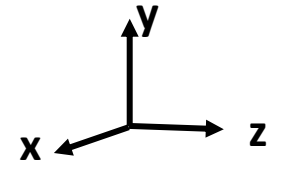
The latest tape-out optimized  $n^+$  strip sensor (W4-AC-D9, 2 cm,  $n^+$  dose = 0.1 p) achieved a spatial resolution of  $\sim 1.4 \mu\text{m}$ .

# Sensor Spatial Resolution Using Different Amplitude Estimators (0.2% Laser)

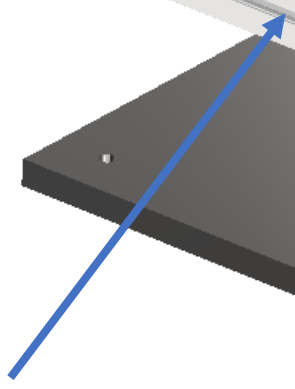


Achieving a spatial resolution below 10  $\mu\text{m}$  using LATRIC's Time-Over-Threshold (TOT) information with a 100  $\mu\text{m}$  strip pitch appears to be challenging and may offer limited flexibility.

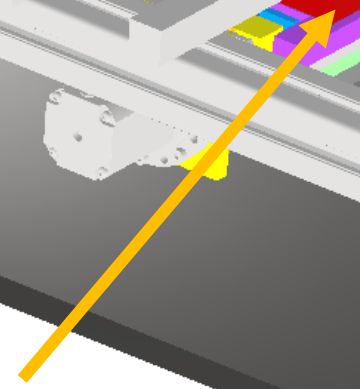
extra PCB frame



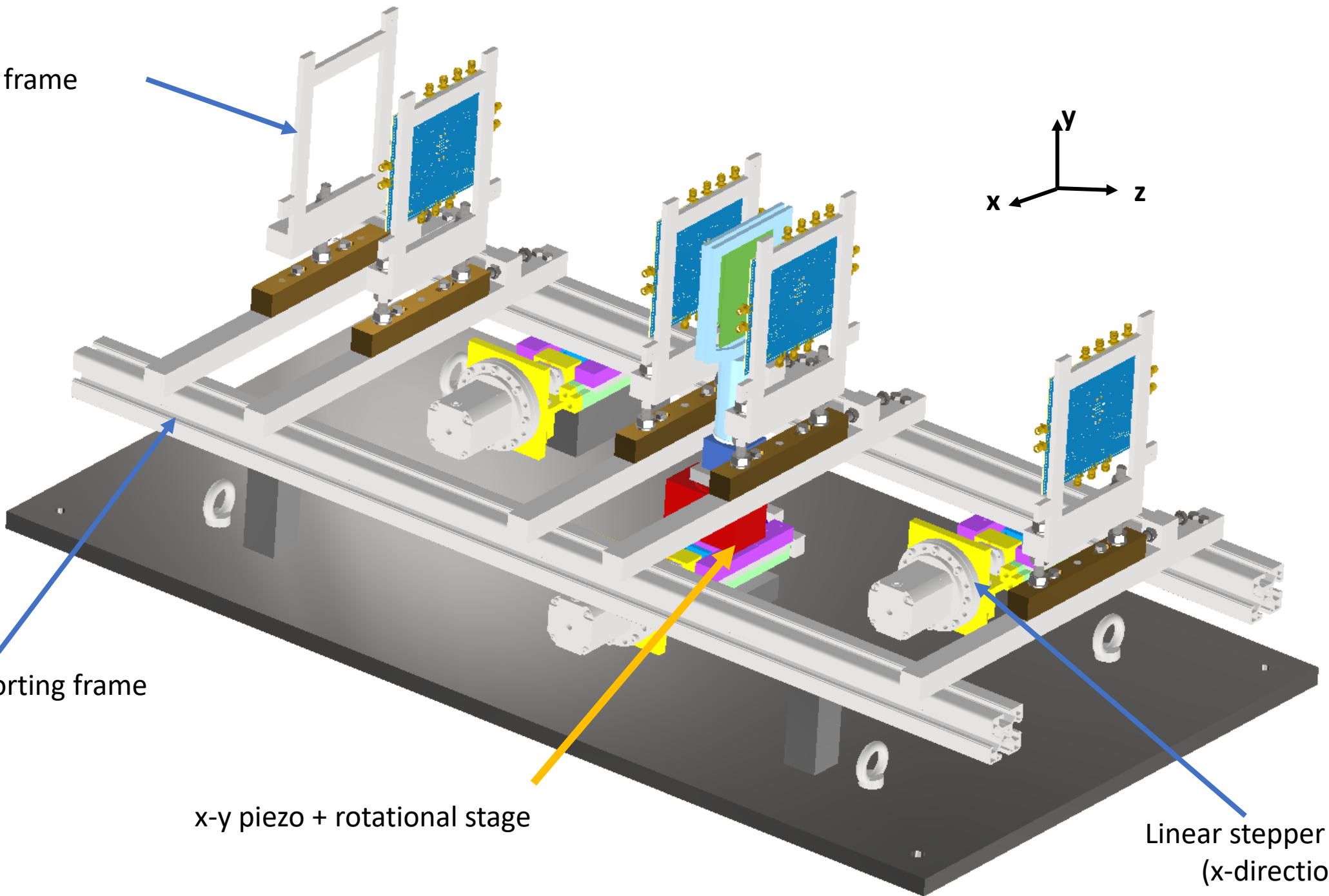
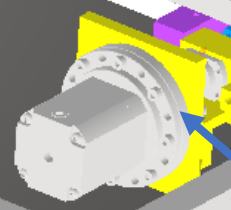
Supporting frame



x-y piezo + rotational stage



Linear stepper motor  
(x-direction)



Height adjustment

X-adjustment

